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A DYNAMIC CONTROL SYSTEM FOR HEATING, VENTILATING AND AIR
CONDITIONING

by

(C) Douglas Kooiman Spratt

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
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Abstract

A dynamically operated heating, ventilating and air-conditioning system can result in minimal energy expenditure when its associated computer control strategy is optimally implemented. From the concepts of free cooling, thermal manipulation and space temperature drifting, relevant theory is developed and translated into generalized algorithms applicable to state-of-the-art computerized control systems. These algorithms were applied to an existing energy management system which controls a University of Alberta building in Edmonton, Alberta. In tests between May and November, 1984, daytime free cooling occurred when outdoor temperatures were between 4°C and 22°C. Thermal manipulation could only be applied during nonoccupancy periods, for which precooling was used. The prediction program incorporated in the precooling strategy was successful in using outdoor air and average building mass temperature forecasting algorithms to determine the duration of precooling. Despite increased space temperature variations associated with dynamic control, comfort conditions improved, due to a reduction in maximum interior temperatures. A longer period of monitoring is required to establish any energy savings due to this installation.

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Nomenclature

$\{ \}$	denotes column vector ($n \times 1$)
$\{ \}^T$	denotes row vector ($1 \times n$)
A	area, m^2
a, b	Fourier cycle coefficients
C	flow coefficient
Cp	specific heat, $KJ/Kg^\circ C$
D	length of crack (m) or area of surface, m^2
E	entrance-way factor
Ech	thermal energy charged, J
Edf	total energy in excess, J
Eod	occupancy distribution energy, J
Epd	preoccupancy distribution energy, J
Es	predicted thermal energy savings due to preoccupancy operation, J
Est	thermal energy stored at beginning of occupancy, J
Eth	thermal energy consumed, J
Etot	daily total HVAC energy, J
g	room transfer coefficient
Ic	total clear-sky horizontal solar radiation, $J/s \cdot m^2$
Idn	direct normal radiation, $J/s \cdot m^2$
Ids	diffuse radiation, $J/s \cdot m^2$
It	total incident solar radiation, $J/s \cdot m^2$ variable for calculating space temperatures, defined by Equation (3-13)
Ith	total horizontal radiation, $J/s \cdot m^2$

I_x	generalized radiation variable, $J/s \cdot m^2$
i	counter for number of hours beyond real time, ($i=1,2,3,\dots$)
j	$j=1$ for cooling season, and $j=2$ for heating season
j_m	heat energy flux, $J/s \cdot m^2$
j_n	work energy flux, $J/s \cdot m^2$
K	room temperature drift rate, $^{\circ}C/s$
K'	temperature drift rate with no air conditioning, $^{\circ}C/s$
$\hat{K}$	estimated room temperature drift rate, $^{\circ}C/s$
$\bar{K}$	moving average temperature drift rate, $^{\circ}C/s$
K_m	mass temperature rate, $^{\circ}C/s$
L	volumetric flow rate, m^3/s
N	flow exponent
n	total number of regressors in a model real-time hourly counter ($n=1,2,3,\dots$) current day
P	theoretical air pressure, Pa
p	room transfer coefficient
Q_{ac}	heat transfer rate from air-handling systems, J/s
Q_d	thermal load differential between Q_{ac} & Q_n , J/s
Q_{df}	load in excess of free-cooling capacity, J/s
Q_{er}	rate of thermal energy depletion, J/s
Q_f	free-cooling capacity heat transfer rate, J/s
Q_i	internal cooling load, J/s

Q_n	heat transfer rate from all natural heat gains and losses, J/s
s	weighting factor
T	temperature, °C
ΔT	difference in dry-bulb temperature of incoming air and leaving air, °C
T^*	empirical predictive temperature, used for daytime control, °C
T_a	dry-bulb temperature, °C
T_a'	assumed constant space temperature, °C
$\bar{T}_a$	empirical dry-bulb temperature, °C
$\bar{T}_{acr}$	critical value of $\bar{T}_a$, °C
T_b	base temperature, as defined in Equation (4-2), °C
ΔT_d	temperature rise of air across supply fan, °C
ΔT_f	temperature rise under maximum free cooling, °C
T_m	interior average mass temperature, °C
T_o	outdoor dry-bulb temperature, °C
$T_{o_{max}}$	forecasted maximum outdoor temperature, °C
T_r	weighted mean radiant temperature of surrounding surfaces, °C
t	time, s
Δt	calculated duration of precooling operation, s
t_w	duration of warmup period, s
t_{sh}	duration of shutdown status during occupancy, s
V	volume, m ³
w	cycling frequency, cycles/hour

Greek Symbols

α	regression coefficient $Ta'(\Sigma g_i)/g_o$
β	regression coefficient g_i/g_o
γ	p_i/p_o
Δ	difference
ϵ	solar altitude, radians
η	proportionality constant
θ	resultant temperature, °C
θ_d	desired resultant temperature, °C
θ_i	initial resultant temperature, °C
θ_{tj}	desired resultant temperature at end of occupancy, °C
λ	solar importance factor
π	constant, 3.1415926535...
ρ	density, Kg/m ³
Σ	summation
v	air delivery flow rate, m ³ /s
ϕ	constant autoregressive parameter
x	generalized independent variable

Subscripts

0	mean
1	annual cycle
7	value at 7:30
365	daily cycle
730	half-daily cycle
i	counter (i=1,2,3,...)
n	counter (n=1,2,3,...)
t	time

Superscripts

j	j=1 for cooling season, j=2 for heating season
---	--

1. INTRODUCTION

Energy conservation is a concern shared by many. At national and international levels, energy conservation can manifest better utilization of resources. At the corporate level, a reduction in energy can lead to reduced operating costs. Since buildings consume roughly one-quarter of Canada's total energy use, they have become a major target for energy conservation studies.

A number of avenues are available to conserve energy, some more financially attractive than others. One area which is receiving increased interest is energy management through computer control. In institutional and commercial buildings, heating, ventilating, and air conditioning (HVAC) systems are often controlled by microprocessors and a central processing unit. Since the rate of energy use ultimately depends on controller signals, a computing system's operating strategy has direct consequences on energy consumption.

An HVAC strategy called *dynamic control* offers great potential in energy use reduction by recognizing three factors:

1. There are certain periods when a building's air-handling system theoretically requires no heating or cooling inputs.
2. The interior mass of a building can act as a thermal storage medium.
3. There exists a time-dependent range of comfort

conditions which the occupants of a building find acceptable.

These three factors can interact to achieve maximum efficacy. Thermal inertia (the second factor) can be used to store or release energy during "free cooling" periods. Accepting a comfort range (the third factor) rather than a fixed temperature can help extend the periods when an air-handling system requires no thermal energy inputs.

The purpose of this thesis is to determine how this dynamic control strategy can be optimally implemented. The optimization parameters (to be minimized) considered were: (1) total primary energy use, (2) manpower, (3) resources, and (4) complexity.

First attempts at implementing dynamic control (as defined above) were published by Hartman (1980)¹. The concept of outdoor balance temperatures was used to demonstrate conditions which would permit free cooling. Major factors (e.g., heat storage capacity, type of HVAC system, hours of building use, etc.) affecting building control were investigated. Despite its claimed energy savings, additional literature about dynamic control has been sparse. Most recently, Holmes (1983) in his energy management case study noted:

¹ "Free cooling" in this thesis refers to an air-handling system's ability to supply air without the addition of thermal energy. That is, *heating and cooling* requirements of a zone are met by unconditioned air. Free cooling is "free" in the sense that no thermal energy is used; however, energy is still required to distribute the air.

² References appear at the end of the thesis.

The most significant information gained to date is in the area of the effect of mass on building thermal response and the energy savings potential when managing that mass with a 'smart' control system that can use historical data along with weather patterns and forecasts to anticipate the building response and system operation Required to maintain the desired conditions.

(Page 18)

The present study attempts to bridge the founding concepts of dynamic control with its sound application to real HVAC control systems. Free cooling, thermal inertia, and comfort bound concepts were theoretically developed, then translated into pragmatic applications for state-of-the-art control systems.

A major difficulty arises in translating the theory of dynamic control to its practical application. In any building, the operation of an HVAC system is dependent upon dynamic heat transfer processes. Most control strategies require only limited knowledge of these processes, since they are steady state in character³. However, since dynamic control attempts to manipulate the thermal state of a structure, a greater knowledge of these heat transfer processes is required.

³ That is, control adjustments are based on real-time measurement of deviations from set point.

Unfortunately, the pattern of heat exchanges that take place in and around any real enclosure is complex. Additionally, the real-time computing capacity of existing control systems is quite limited. One is therefore faced to resolve the question: *to what extent can modelling of these thermal processes be simplified while ensuring maximum energy savings?*

The present work examines the alternatives available for this optimization problem, and provides logical solutions, ultimately evaluated by field measurements from a pilot building. Chapter 2 establishes the objectives and constraints of an HVAC control system, and presents an overview of dynamic control. Chapter 3 theoretically develops the concepts of free cooling, thermal inertia, and interior temperature drifting, and considers their application to current HVAC control systems. The experimental portion of this study is covered under Chapters 4 and 5. In Chapter 4, changes made to an existing university campus building to permit dynamic operation are documented. Chapter 5 presents and discusses the findings from installation monitoring. This is followed by conclusions drawn from the study.

2. CONCEPTS OF CONTROL

To determine how dynamic control should be implemented, it is necessary to understand the essential concepts of environmental control. This chapter acts as a foundation for understanding subsequent chapters, by answering the following questions:

1. What is the purpose of HVAC control?
2. How does dynamic control achieve this objective?

The following sections answer these questions by identifying control objectives and reviewing the principles of dynamic control.

2.1 Control Objectives

In developing any control strategy, it is essential to first identify the true objectives at hand, and then to determine the constraints and limitations faced. Based on these objectives and constraints, an appropriate strategy can be developed to achieve the objectives and adhere to the constraints.

With environmental control, objectives and constraints are dependent on the viewer. Normally three viewers exist:

1. the control designer,
2. the building owner, and
3. the occupant.*

Traditionally, the control designer's objective has been to

* In this study, it is assumed the owner pays the utility bills, while the occupant's rental fee is not directly linked to energy use.

produce a control system which corrects deviations as quickly as possible, while maintaining stability (Wolsey, 1975). Such a strategy would invoke maximum comfort. More realistically, the designer must satisfy the demands of the financial investor (i.e., the owner).

A building owner's objective is to minimize operating costs, while maintaining satisfactory comfort conditions. (Now comfort is defined as a constraint rather than an objective.) The monetary objective of operating cost minimization can be translated into technical objective(s) if the following variables are taken into account:

1. Capital investment.
2. Payback time, or other monetary policy indicator.
3. Unit energy costs.

Unfortunately, the significance of these variables cannot be generalized, as they depend on local factors, government policies, et cetera.

Accepting these uncertainties, it is possible to translate the owner's objective into the following pursuit: *to maintain a control system which minimizes energy use, while maintaining occupancy comfort.* This objective was used to evaluate proposed control strategies.

In order to develop a control strategy based on identified objectives and constraints, it is necessary to define these parameters. The remainder of this section quantifies energy use and comfort by posing two questions: (1) what energy is to be minimized? and (2) what constitutes

satisfactory comfort conditions?

What energy is to be minimized? Figure 2.1 shows the thermal processes and associated levels of HVAC control in buildings. Dynamic control and other control strategies to be discussed manipulate the distribution system, which uses thermal (steam, chilled water, etc.) and electrical energy inputs. Therefore, these inputs should be minimized.

What constitutes satisfactory comfort conditions? If a control system uses comfort as a constraint, it is necessary to know what limits will be acceptable to the building population. Two conditions of comfort exist which must be quantified: steady-state and dynamic.

Considerable research has been performed in the area of thermal comfort under steady environmental conditions. Both Fisk (1981) and ASHRAE (1981) have given extensive reviews of past work, and have noted the following:

1. Human comfort is dependent on heat generation within the body and energy exchange with the environment.
2. The energy transfer modes experienced between a body surface and the environment are evaporation, convection, and radiation.
3. The environmental factors which affect the rate of these modes are
 - a. dry-bulb temperature,
 - b. surrounding surface temperatures,
 - c. moisture content of the air,

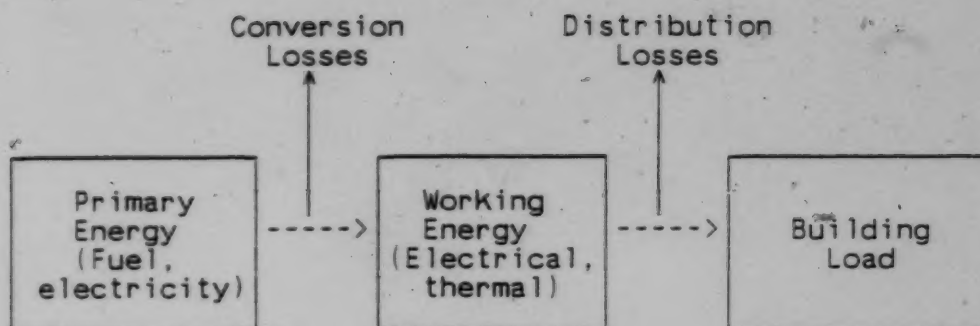


Figure 2.1a Thermal processes.

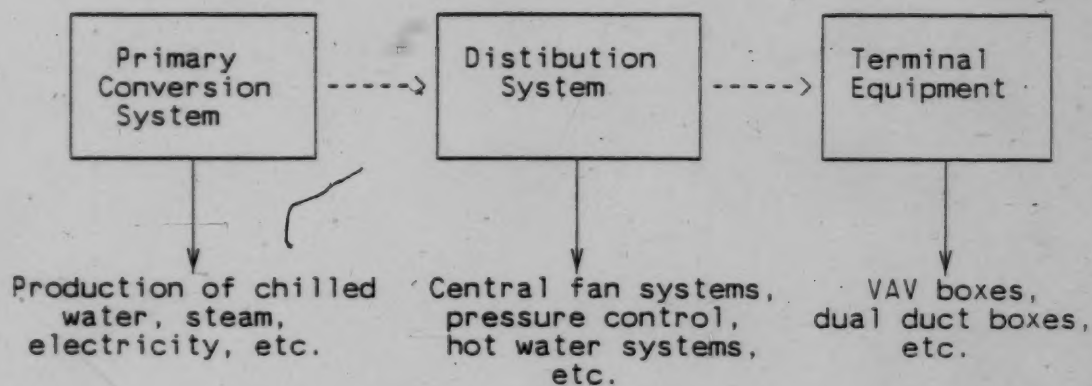


Figure 2.1b Levels of HVAC control.

- d. movement of air across the human body, and
- e. solar radiation.

Occupants often believe that room dry-bulb temperature is the only environmental factor which affects their comfort; however, this ignores the effects of items (b) through (e) above.

In an attempt to account for one or more of the aforementioned environmental factors, various environmental indices have been proposed. ASHRAE (1981) has divided these indices into three classes: (1) direct, (2) rationally derived, and (3) empirical, as detailed in Table 2.1.

To maintain comfort and evaluate control alternatives, it is necessary to select and monitor an appropriate index. The effective temperature (an empirical index) has been the best known and most widely used of all thermal indices. It combines the effects of dry-bulb, wet-bulb, and air movement to yield equal sensations of warmth or cold. However, it has been rejected for this study because: (1) radiative effects are not accounted for, (2) humidity and air movement are difficult to measure, and (3) humidity variations typically experienced in buildings do not greatly affect comfort conditions (Fisk, 1981). Instead, an empirical index called the resultant temperature (Fisk, 1981) has been chosen. It recognizes body heat losses from convection and radiation exchange, using the formula

$$\theta = 0.5(T_a) + 0.5(T_r) \quad (2-1)$$

Table 2.1 Environmental control indices.

CLASS	INDEX
Direct Indices	Dry-bulb temperature Dew-point temperature Wet-bulb temperature Relative humidity Air movement
Rationally Derived Indices	Mean radiant temperature Operative temperature Humid operative temperature Heat stress index
Empirical Indices	Effective temperature Environmental temperature Black globe temperature Corrected effective temperature Wet-bulb globe temperature Wind chill index

where:

- θ - resultant temperature,
- T_a - dry-bulb temperature, and
- T_r - area weighted mean radiant temperature.

The comfort bounds acceptable to occupants varies from building to building, due to the types of work performed, and the clothing levels used. There is also evidence that the desired environmental temperature for a building will vary from season to season (Fisk, 1981). However, upper and lower limits of comfort can be determined for existing buildings by occupant surveys.

Little work has been done to study the effects of thermal transients with drifts in dry-bulb temperature and humidity on comfort, and occupant acceptability of such procedures is unclear. Table 2.2 summarizes various studies on the effect of temperature fluctuations on comfort. It seems plausible that a maximum rate of temperature change of 0.75°C/h should be acceptable under most conditions. Fisk (1981) has found relative humidity variations between 40 and 70% do not affect comfort conditions significantly. Therefore, this study will consider temperature drifts only, and set a criterion of 0.75°C/h maximum drift rate.

In summary, the most appropriate control objective found for strategy development and evaluation was to reduce operating costs by minimizing energy consumption, provided that interior environmental temperatures do not go outside specified bounds or change at a maximum specified rate.

2.2 Overview of Dynamic Control

With control objectives defined, the theoretical merit of dynamic control can be identified. This section presents an overview of dynamic control's approach to minimum energy use and comfort criteria.

Dynamic control is a strategy which integrates three concepts:

1. free cooling,
2. interior temperature drifting, and

Table 2.2 Effects of drifts in temperature on comfort.

Reference	Conditions of Test	Findings
Sprague and McNall (1970)	(1) Population group with C_{lo} values of 0.6 were used in tests of thermal drifts. Test periods were 3 hours each. (2) In another study, 16 different tests on temperature drift with different fluctuation periods were performed.	No serious complaints should occur due to temperature fluctuations if $(\Delta t^2)w < 4.63$ where (Δt) = the peak to peak amplitude of the temperature fluctuation, deg. C and w = the cycling frequency, cycles/h.
Griffiths and McIntyre (1974)	Subjects were exposed to slow one-directional temperature changes, centred around 23 deg C over a 6 h period.	A maximum rate of temperature change of 0.75 deg C/h with a maximum deviation of 2.25 deg C from the mean comfort temperature was recommended.
Berglund and Gonzalaz (1978)	Subjects were exposed to space temperature changes in both directions from a neutral point, over a 4.5 h duration.	A 0.50 deg C/h rate of change from a base temperature of 25 deg C was acceptable to 80% of the occupants.

3. thermal flywheeling.

Most buildings today employ some form of free cooling. Controllers usually regulate the portion of outdoor air introduced according to its enthalpy and the zone cooling demands. This so-called economizer cycle only deals with outside air control, as shown in Figure 2.2. Dynamic control takes the idea of free cooling one step further by also considering the air-handling system. Whenever possible, thermal energy is neither added nor removed.

Although disallowing thermal inputs (cooling or heating) helps minimize energy expenditure, it will only produce a targeted interior environment between certain outdoor air temperatures, known as balance temperatures. Beyond these limits, interior temperatures will drift from their set-point values. However, Hartman (1980) has suggested that free cooling may be employed beyond the balance temperature range if space temperature drifting between time-dependent comfort bounds is permitted⁵. This measure will enhance energy savings, while still maintaining an acceptable environment.

Outdoor air limits for free cooling can be further extended by storing and releasing thermal energy. Traditionally, thermal energy for control purposes only considered the use of a specialized space under, above, or within a building. More recently, the building's own mass

⁵ Temperature comfort bounds may be enlarged at the beginning and end of occupancy, when occupants are either anticipating impending comfort enhancement, or preparing to leave.

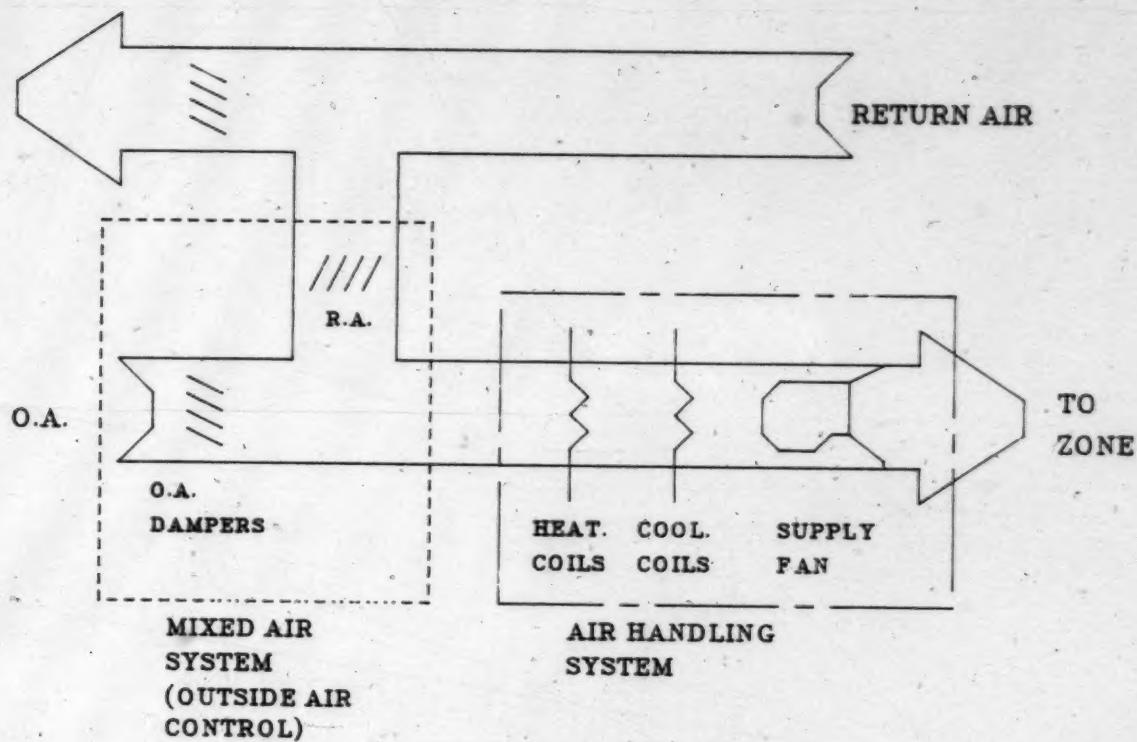


Figure 2.2 Typical distribution system divisions.

has been used as a thermal storage medium.

Now that the conceptual elements of dynamic control have been covered, an example is presented to integrate these principles into a system strategy. Figure 2.3 shows an idealized 24 hour period of operation. The building's environmental control system uses four modes of operation for this day: (1) off, (2) precooling, (3) warmup, and (4) free cooling. Outdoor air, space, and average building mass temperatures are plotted, along with the building system's balance temperatures and interior comfort bounds.

After midnight, with the air-handling system off, the control system's computer calculates the number of hours of precooling required before occupancy. This time span is determined by predicting the thermal load and equipment cooling capacity during occupancy.

At 4:00, the computed precooling duration time is equal to the actual duration remaining before occupancy. Therefore, the system is turned on and precooling is initiated. Since the outdoor air is between the upper and lower balance temperatures, no primary thermal energy (e.g., chilled water) is required for precooling operation. One hundred percent outdoor air is used to supply maximum cooling.

After 4:00, both the building's air mass and building mass' temperatures are lowered. This action precools the building so that cooling loads later in the day can be

* A building's mass includes all floors, walls, furniture, etc.

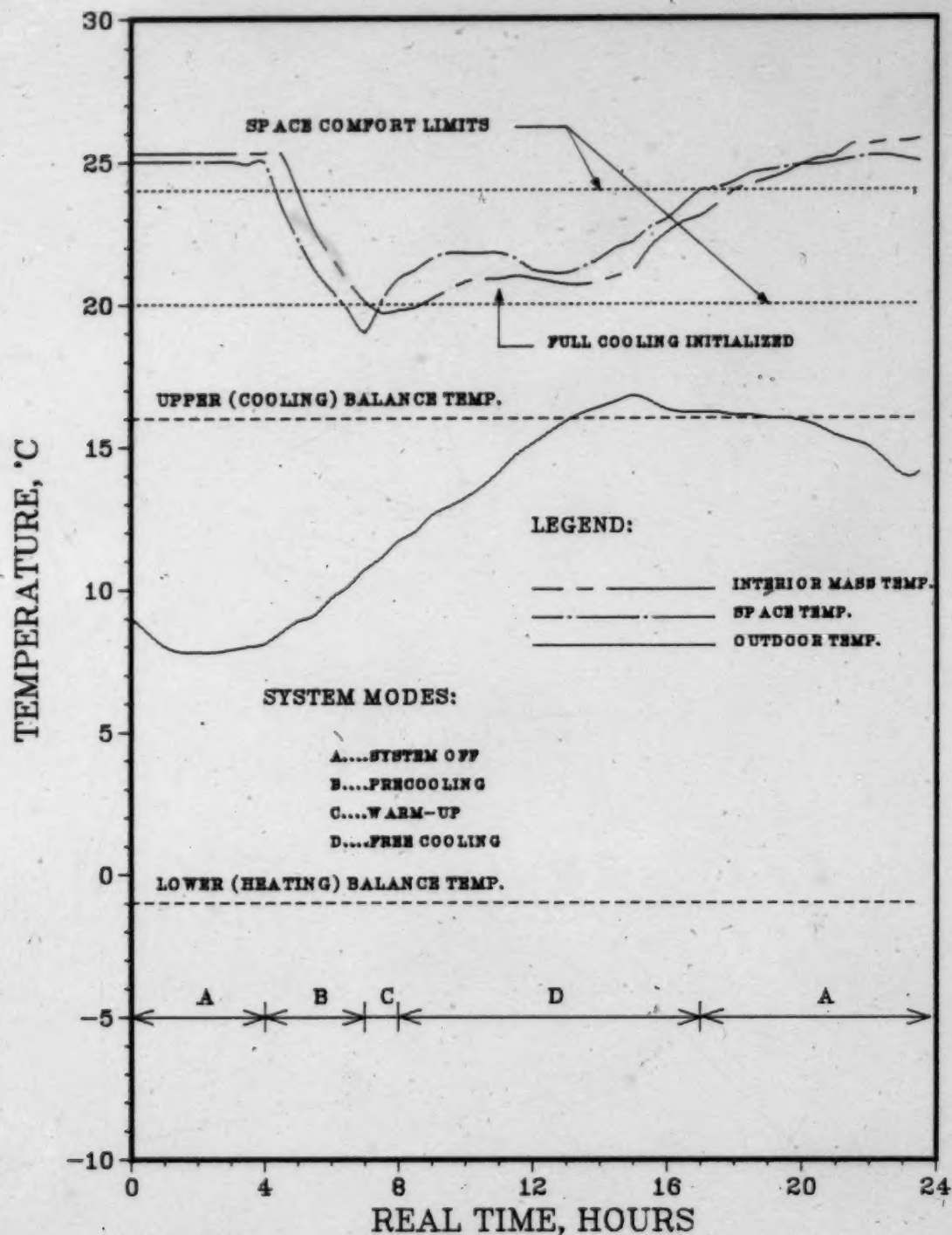


Figure 2.3 Idealized 24 hour trend of dynamic control operation.

partially absorbed by the structure.

During this precooling, the system's computer calculates the required duration of warmup. This is a function of interior temperatures and system heating capacity. The duration computed in this example is one hour, so that the warmup cycle is initiated at 7:00.

From 7:00 to 8:00, maximum heating is supplied by using 100% recirculated air. This action quickly raises just the air temperature above the lower space comfort limit (i.e., 20°C) to ensure an acceptable environment as first occupants arrive. The building's mass does not follow the space temperature rise immediately due to the effects of thermal inertia.

At 8:00, occupants enter the building to find an acceptable environment, though slightly cool. The control system is switched to free cooling mode, with thermal energy inputs remaining disabled. Outdoor and return air dampers are adjusted to supply a mixed air temperature which satisfies zone cooling loads and ventilation requirements. A mean space temperature of 21.7°C is maintained.

During this free-cooling mode, the system's computer periodically predicts when interior temperatures will begin drifting, and the magnitude of such drifts. At 11:00, predictive calculations indicate space temperatures will drift above the upper comfort bound before occupants leave, unless corrective action is taken. Therefore, full economy cooling is introduced to lower the mean space temperature to

21.2°C. By 12:30, occupants feel slightly cool, though no complaints are made. At 13:00, the building cooling load exceeds the free cooling capacity of the air system, so that space temperature elevation commences. However, due to the lowered set-point between 11:00 and 13:00, interior temperatures only exceed the upper comfort bound after occupancy (without the application of cooling coils).

During the hours preceeding 5:00, the computer calculates the earliest possible time to turn the HVAC system off. This duration is dependent on the existing space temperatures and the temperature drift rate. For the case illustrated in Figure 2.3, the average space temperature can only be held within the comfort limits if the system remains on until 17:00. The 24 hour cycle is completed by permitting space and mass temperatures to drift freely (within limits critical to the building and its systems) with the air-handling system off.

In summary, dynamic control attempts to minimize energy use by:

1. disabling thermal inputs whenever possible,
2. precooling during unoccupied periods, and
3. allowing space temperatures to drift within defined comfort bounds.

Chapter 3 will develop each of these principles from conception to practical application.

3. STRATEGY DEVELOPMENT

To determine how dynamic control can be optimally implemented, its founding concepts must be (1) reviewed in principle, (2) theoretically developed, and (3) refined for practical application. Chapter 2 reviewed the principles of dynamic control; this chapter theoretically develops the concepts of free cooling, thermal inertia, and interior temperature drifting, and considers their application to state-of-the-art HVAC control systems.

3.1 Free-Cooling Operation

Free cooling permits the disabling of thermal inputs within an environmental control system. Of all air-handling operational modes, it has the lowest energy use rate and should be utilized whenever possible.

This section will first address the theory of maximizing free cooling use, followed by an analysis of its application to various HVAC systems.

3.1.1 Theory

To determine how to maximize its use, it is instructive to review the thermodynamics of free cooling. HVAC engineers, when sizing air-handling units, have used the concept of a balance temperature range to schedule economizer use. See, for example, Perkins (1984). This balance temperature concept can be extended to free cooling applications, and is used as a starting point for explaining

free cooling.

Consider an air-conditioned zone within some defined control volume, as shown in Figure 3.1. Supposing constant temperature is desired, the rate of heat transfer to the zone air must be zero. Therefore,

$$Q_{ac} - Q_n = 0 \quad (3-1)$$

where:

Q_{ac} - heat transfer rate from the controlled air handling systems, and

Q_n - heat transfer rate from natural heat gains and losses, such as lighting, people, equipment, solar radiation, infiltration, and envelope conduction.

Or,

$$Q_{ac} = Q_n \quad (3-2)$$

In design work, Q_n is assigned two critical values--a maximum, corresponding to summer cooling design, and a minimum, for winter heating design'. For a given air-handling system, the corresponding critical values of Q_{ac} can be met by free-cooling operation alone if the outdoor air is within a certain enthalpic range, called the balance temperature range'.

' For the purpose of this discussion, Q_n for winter design also includes heat gains from water-to-air heating systems, such as perimeter radiation systems.

' The effect of moisture content on outdoor air enthalpy is occasionally ignored when ambient humidity is low.

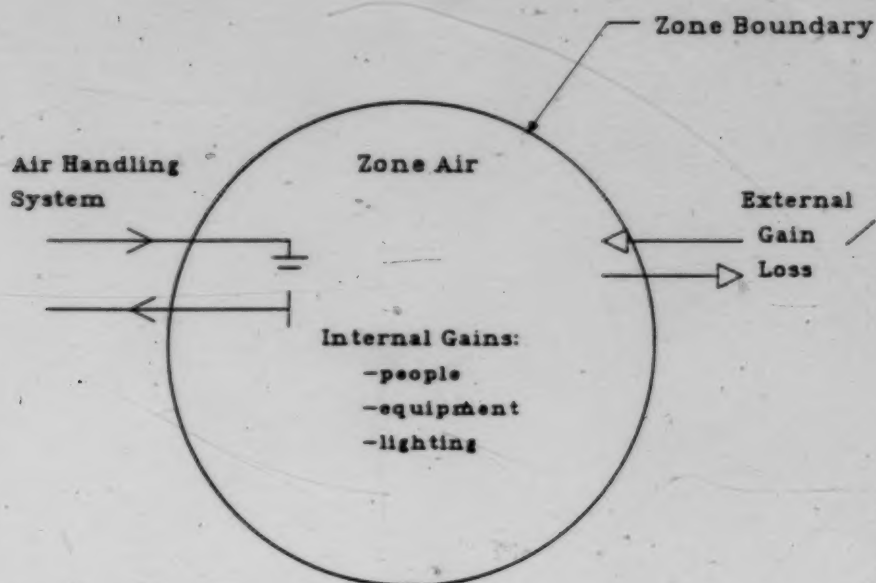


Figure 3.1 Typical zone energy balance.

This balance temperature concept is shown in Figure 3.2. For summer design conditions, point A represents the outdoor temperature at which Q_{ac} can be met, with the outdoor air damper set at a minimum; conversely, point B represents 100% outdoor supply for the critical heat transfer rate. The temperatures for points A and B are defined as the heating and cooling balance temperatures (for critical summer design) respectively.

In reality, the actual (effective) balance temperatures for an air-handling system are different from those shown in Figure 3.2, for the following reasons:

1. Environmental control is a dynamic process.
2. Air-handling units usually manage more than one comfort zone.

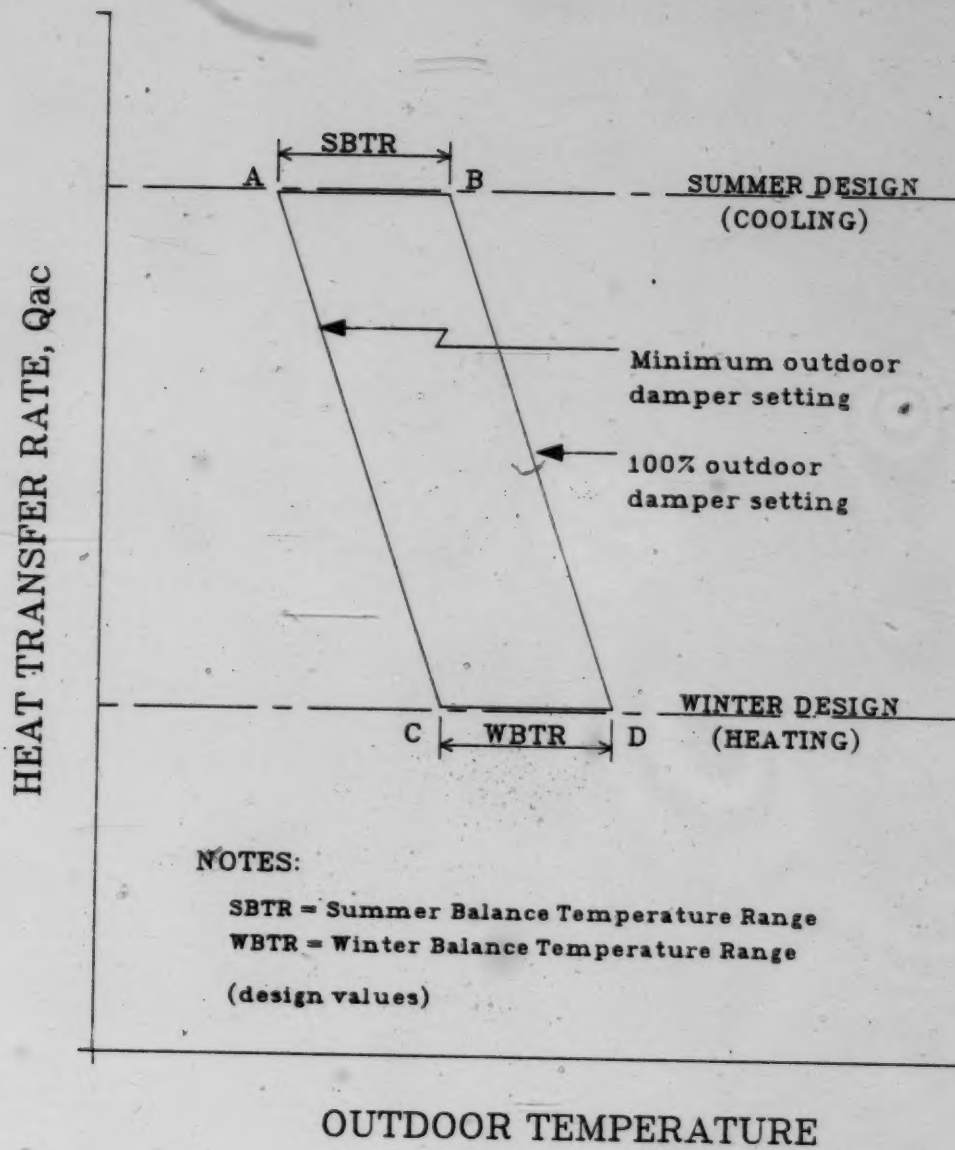


Figure 3.2 Design balance temperatures.

3. Perfect room air distribution never exists.

Dynamic processes. For many buildings, a steady-state set point within a zone is not required; rather, a temperature range can be permitted. Secondly, building loads fluctuate daily and annually within design values of Q_{ac} . Both interior temperature drifting and thermal load fluctuations tend to alter the balance temperature range.

Zone variations. It is common practice to have an air-handling unit supply air to several comfort zones. Since each zone has a different range of heating/cooling requirements, their respective balance temperatures will be different. Therefore, the outdoor temperature range which satisfies comfort control in several zones simultaneously is smaller than when only one zone is of concern.

Room air distribution. The definitions of design balance temperatures were based on a zone with uniform air temperature. However, in reality, uniform temperatures do not exist. McQuiston and Parker (1977) warn that discomfort may arise due to excessive room air temperature variations (horizontally, vertically, or both) or excessive air motion (draft). These imperfections may require altering the supply air temperature, which would in turn change the balance temperatures.

The effects of the aforementioned factors on balance temperatures is summarized in Table 3.1. Only interior temperature drifting increases the effective balance temperature range (EBTR). Conversely, only multiple zoning

Table 3.1 Conditions affecting balance temperatures.

CONDITION	EFFECT ON BALANCE TEMPERATURES
Interior temperature drifting.	Balance temperature range increased. Heating balance temperature lowered. Cooling balance temperature raised.
Daily and annual load variations.	Heating and cooling balance temperatures vary with equal magnitude and direction over time, within winter and summer design conditions. Magnitude of balance temperature range constant.
Multiple zoning.	Balance temperature range decreased.
Room air distribution imperfections.	Heating and cooling balance temperatures both lowered or raised in equal magnitude. Magnitude of balance temperature range (for single zone) unaltered.

reduces the range. The remaining factors (load variations and room air distribution imperfections) by themselves do not alter the magnitude of the EBTR. However, if an air-handling unit controls more than one zone, these factors will reduce the range.

As an example, consider two zones, *A* and *B*, controlled by one air-handling unit (AHU). Both zones are thermodynamically similar, apart from zone *B* having excessive drafts. To maintain equal comfort, zone *B*'s room air temperature must be higher than *A*'s. This implies that the required cooling delivery rate, Q_{ac} , to each zone will be different, as shown in Figure 3.3. If no drafts existed in zone *B*, its value of Q_{ac} would be the same as for zone *A*, so that the balance temperature range would be from points 1 to 2. However, with the room distribution imperfection, the AHU's EBTR range is only from points 3 to 2.

In summary, balance temperature concepts show that free cooling can be applied only during a specific outdoor enthalpic range. This range can be enlarged by temperature drifting'. Conversely, it will be diminished if an AHU must handle zone variations. Room air distribution imperfections and load variations can further augment problems of free cooling with multiple zoning.

' See Section 3.3 for details on temperature drifting.

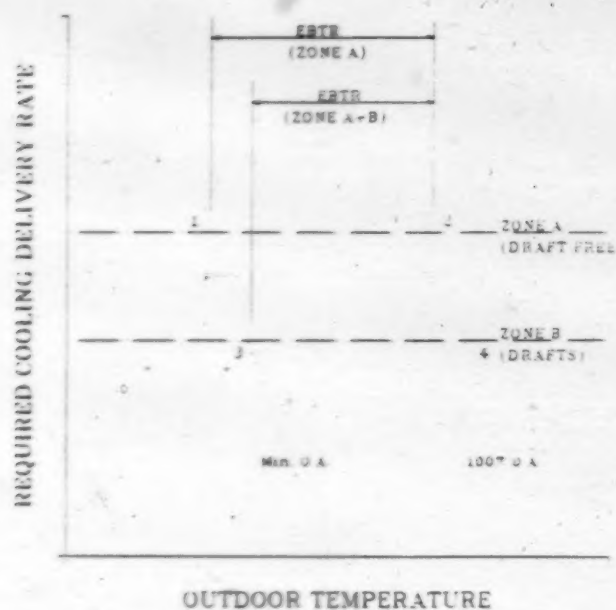


Figure 3.3 Effect of zone variation on balance temperatures.

3.1.2 Practical Application

With the theoretical aspects considered, it is now possible to discuss how free cooling can be applied to real HVAC systems. The major options available to an HVAC designer can be studied to determine how to maximize free cooling use, and how free cooling alters a system's operation.

Thermal energy can be spent at both central and terminal (i.e., zone) locations. Central HVAC systems introduce thermal energy to meet overall building conditioning requirements, whereas terminal systems use thermal energy to satisfy zone variations.

Central HVAC systems. The major classifications given

to central air systems are:

1. single-path versus dual-path, and
2. constant volume versus variable volume.

The ramifications of free cooling with each of these options are discussed.

Providing that the outdoor temperature is within the EBTR, the disabling of thermal inputs (e.g., heating and cooling coils) will not greatly affect a single-path system. This is not true of dual-path systems. Free cooling operation will (1) eliminate a dual-duct system's ability to address zone variations at the central level, and (2) significantly reduce its thermal energy consumption. This is because a dual-path system, when operating under free-cooling mode, supplies identical air temperatures to both ducts. Therefore, under free cooling, a dual-duct system is thermodynamically equivalent to a single-path system.

When comparing central-air systems of equal capacity, variable-air-volume (VAV) systems will have a larger effective balance temperature range than constant volume systems. The effective heating balance temperature for a VAV unit will be lower, since the rate of air supply can be reduced. On the other hand, constant-volume systems cannot reduce their air delivery rate, so that heating requirements beyond the minimum outdoor damper setting can only be achieved by adding heat.

Terminal HVAC systems. To meet intra- and inter-zone variations, terminal units supplement or alter the cooling/heating supplied from central air systems. These units can be divided into two categories; namely:

1. those units requiring thermal inputs, and
2. those not requiring thermal inputs.

Table 3.2 categorizes accordingly the terminal systems used in industry.

The requirement of thermal energy in terminal systems is a critical factor under free cooling. Units which normally use thermal energy will become ineffective during free cooling, whereas, units in the other category will be able to handle zone variations under all operational modes.

For the designer, it is important to realize that terminal systems which don't use thermal energy can only handle small load variations. Where large zone variations (e.g., perimeter areas) exist within an HVAC system, terminal units using thermal energy will be required. These units which use thermal energy will not be able to address zone variations during free cooling, thereby allowing for possible discomfort.

In conclusion, HVAC systems which accomodate zone variations through thermal energy use will lose their ability to meet these variations during free-cooling operation. Therefore, environmental systems which enhance the duration of free-cooling operation, while maintaining comfort, include the following:

Table 3.2 Terminal HVAC systems.

Units not requiring thermal input(s)	Units requiring thermal input(s)
VAV throttling boxes	Reheat units
Induction units	Forced air units *
Pulsating units	Hydronic systems *
Terminal fans	

* Perimeter heating.

1. Single-path central air systems;
2. Variable-air-volume systems; and
3. Thermal energy-free terminal systems.

Other systems can reduce energy consumption through free cooling, though significant room temperature differences may exist between zones.

3.2 Thermal Inertia

Thermal inertia is the ability of a substance to absorb and release thermal energy over time. The concept of thermal inertia originates from the general energy equation^{1*}:

$$\iiint \partial(\rho C_p T) / \partial t dV + \iint \rho C_p T V dA + \iint j_m dA = - \iint j_n dA \quad (3-3)$$

where:

^{1*} The general energy equation is developed from the first law of thermodynamics. See Lock (1984).

- t - time,
- Cp - specific heat,
- ρ - density,
- A - area,
- T - temperature,
- V - velocity,
- j_m - heat energy flux, and
- j_n - work energy flux.

The first term of Equation (3-3) represents the thermal inertia of a system. Therefore, the essential parameters of thermal inertia must be (1) mass, (2) heat capacitance, and (3) time.

People have long recognized the merit of thermal inertia in buildings under certain climatic conditions. For example, early civilizations in arid climates often built their dwellings with thick stone walls whose temperature cycle would lag the outdoor air by several hours. In this manner, rooms would feel cool during the day and warm at night. More recently, Catani and Goodwin (1976) and others¹¹ have attempted to quantify the merits of thermal inertia in buildings through experiments and simulations. They have suggested energy consumption can be reduced under certain climatic and occupancy conditions by increasing the total heat capacitance of a building envelope.

¹¹ See also National Concrete and Masonry Association (1974), and Portland Cement Association (1974).

In addition to the benefits of thermal inertia in envelope design, researchers have recognized its potential to reduce energy expenditure through use of certain control strategies. Givoni (1978), for example, has noted that heat storage capacity can be utilized to reduce the rate of indoor temperature elevation during occupied hours by:

1. minimizing ventilation during hot hours to allow the structure to absorb heat gains, and
2. maximizing ventilation during the evening to allow the release of daytime heat build-up.

The application of thermal inertia to HVAC control has been a manifestation of energy storage systems in buildings. The first large-scale application of storage for cooling began in Japan during the 1960's, as a result of the need to control time-of-day and peak electric demand charges (Shavit, 1980). Those storage systems, and subsequent systems in North America, used a separate energy reservoir above, below, or within the building.

Rather than employing a separate storage medium, dynamic control uses the building's own fabric to store and release energy. Givoni (1978) states that thermal storage can occur (1) in the exterior envelope (wall and roof) and (2) in the interior (floors, partitions, furniture, etc.) of a structure. However, only the heat storage *within* a structure can be controlled. This is illustrated in Figure 3.4¹², where the external envelope is shown to be

¹² Taken from Fisk (1981).

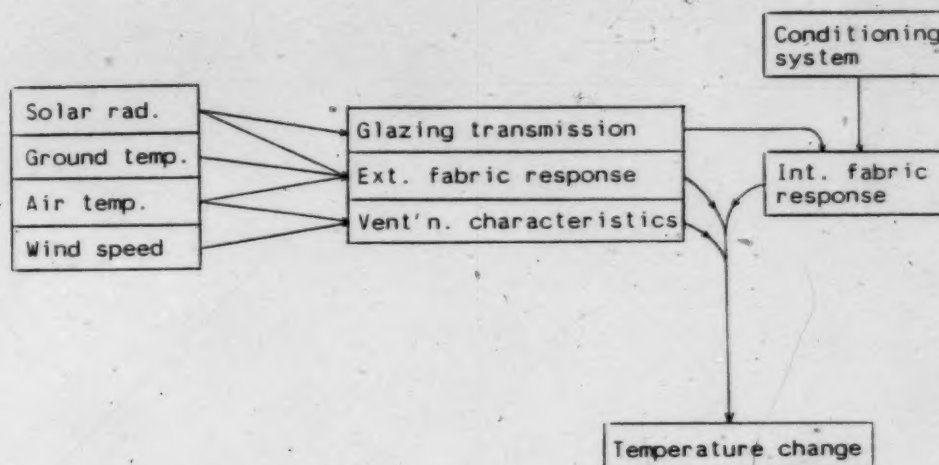


Figure 3.4 Role of fabric in defining thermal inertia.

affected only by the weather, whereas the internal fabric can be controlled by the conditioning system.

Another area in which dynamic control's use of thermal inertia differs from conventional energy storage systems is the level of control. Reservoir systems can directly control the rate of energy depletion; on the other hand, the mass within a building gains or loses heat by largely uncontrollable heat transfer mechanisms.

To successfully apply the benefits of thermal inertia to dynamic control, it is necessary to:

1. understand the interaction between the thermal loads and the conditioning system within a building, and
2. translate the associated heat transfer theory into algorithms suitable for energy management systems.

The remainder of this section will meet these requirements, and discuss both preoccupancy and daytime strategies. As

the pattern of heat exchanges that takes place in and around any real enclosure is complex, special attention will be given to the prediction of thermal loads, and the limitations of available intelligence systems.

3.2.1 Application to Preoccupancy Operation

The most common purpose of preoccupancy operation is to ensure that daytime comfort constraints are realized just before building use. Optimum start strategies assume that preoccupancy energy can be minimized by starting the conditioning system at maximum capacity at the latest possible moment (Fassbender, 1981). However, this is not necessarily an optimal solution, as the effects of thermal inertia are not taken into account.

The thermal manipulation of a building's mass before occupancy will reduce primary thermal energy requirements whenever free cooling is (1) available before occupancy, and (2) only available for limited periods (or not at all) during occupancy. For example, a building requiring daytime cooling can be precooled in the early morning with 100% outdoor ventilation (i.e., full free cooling). The thermal inertia of the structure will permit heat gains later in the day to be partially absorbed by the cooled mass. Without this precooling, daytime heat gains would necessitate the use of cooling coils.

To effectively save energy using the thermal inertia of a building, it is necessary to determine:

1. the time, duration, and magnitude of the heating/cooling load in excess of the HVAC system's free cooling capacity,
2. the rate of (thermal) energy depletion from the mass,
3. the rate of thermal charging of the mass before occupancy, and
4. the optimum amount of energy to be stored.

Excess load. The daytime thermal load in excess of the free-cooling capacity can be estimated by predicting the thermal load profile, $Q_n(t)$, and the free cooling capacity of the HVAC system, $Q_f(t)$. The prediction of $Q_n(t)$ and $Q_f(t)$ is discussed separately under Subsection 3.2.3. Typical profiles of $Q_n(t)$ and $Q_f(t)$ are shown in Figure 3.5. Whenever $Q_n(t)$ is less than $Q_f(t)$, the HVAC system can employ free cooling and maintain comfort constraints. However, from times t_1 to t_2 , Q_n will exceed Q_f , so that either cooling energy must be applied from t_1 to t_2 , or the mass in the zone must be precooled to allow part or all of the excess load to be absorbed. The magnitude of the total energy in excess of Q_f is:

$$E_{df} = \int_{t_1}^{t_2} (Q_n - Q_f) dt \quad (3-4)$$

It should be noted that the period of "excess load" (i.e., t_1 to t_2) corresponds with the period in which the effective balance temperature range is exceeded. If the outdoor air is forecasted to remain within the EBTR during

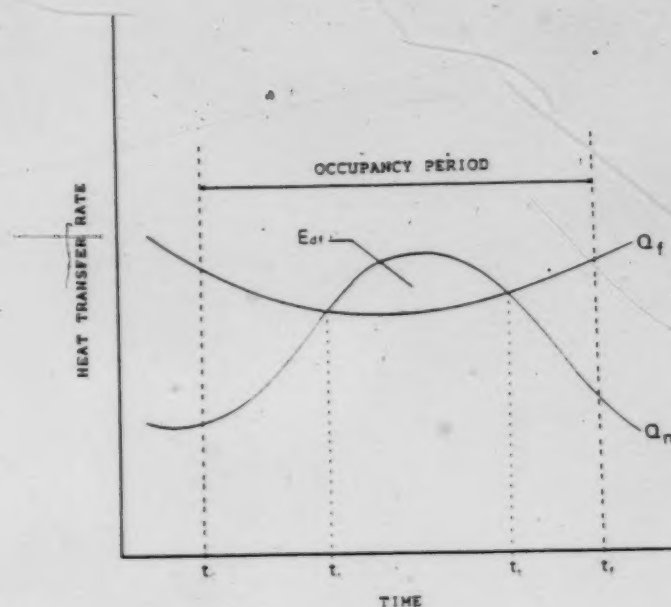


Figure 3.5 Definition of daytime load excess.

the daytime, preoccupancy thermal manipulation will not save energy.

Rate of depletion. From the start of occupancy, the energy stored within a structure will discharge into the surrounding air at some largely uncontrollable rate. Prediction of this depletion rate is necessary in determining (1) how much stored energy will be available when the outdoor temperature exceeds the EBTR of the system, and (2) how much energy will be released during the excess-load period.

The discharge rate of thermal energy within the mass of a building is dependent on four thermal interactions; namely:

1. HVAC - air,
2. air - mass,
3. air - heat gains/losses, and
4. mass - heat gains/losses.

These interactions are shown schematically in Figure 3.6.

Recognizing these four heat exchange patterns, the discharge rate can be predicted by using one or more of the following methods:

1. Simulation studies;
2. Analysis of historical data; or
3. Real-time measurements.

Off-line¹³ studies can help estimate the depletion rate, $Q_{er}(t)$, for various weather and occupancy patterns.

Once the general form of $Q_{er}(t)$ has been studied off-line, an *on-line* algorithm must be developed to predict $Q_{er}(t)$ each day. Given the relatively small computing power of energy management systems (compared to off-line systems), prediction algorithms cannot model the aforementioned heat transfer interactions in detail. This is due to the non-linear and stochastic nature of these processes.

To adjust for the inaccuracies of a simplified prediction model, adaptive control can be employed. While there is no generally accepted precise definition of adaptive control, Asher, Andrisani and Dorato (1976) suggests that:

¹³ "Off-line" refers to tasks not performed on a real-time computing system.

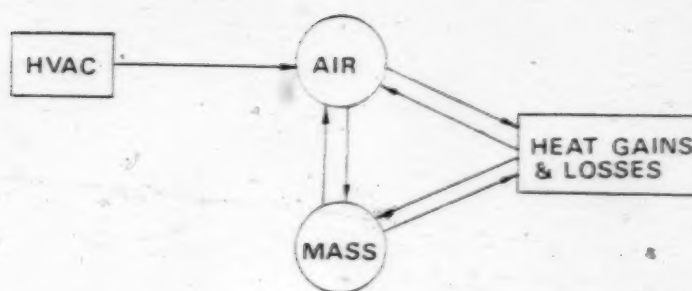


Figure 3.6 Building thermal interactions.

Adaptive control means the control of uncertain systems, with a controller structure that includes a subsystem for the on-line estimation of unknown parameter values or system structure and a subsystem for the generation of suitable control inputs based on estimated parameter values or system structure.

(page 1226)

The general procedure of adaptive control has been called a "learning process" by Kimura (1977), who notes:

The computer acquires data, uses the data for prediction, modifies the data if the data was inadequate, and finds the correct data for control.

(page 257)

Once the structure discharge rate has been predicted, it is possible to estimate the portion of excess load relieved by thermal inertia, for a given amount of initial storage. Hypothetical depletion and excess-load curves are

shown in Figure 3.7. The energy relieved from the excess load is equal to:

$$Es = \int_{t_1}^{t_2} (Qdf)dt + \int_{t_2}^{t_3} (Qer)dt + \int_{t_3}^{t_4} (Qdf)dt \quad (3-5)$$

where:

Es - predicted thermal energy savings due to precooling/preheating,

Qdf - load in excess of the HVAC free-cooling capacity, and

Qer - rate of energy release from the structure.

Rate of charging. Preceding occupancy, the structure must absorb the heating/cooling energy to be released later in the day. The charging rate is dependent on the same heat exchange patterns which govern the rate of depletion. However, the rate of charging is more controllable than the depletion rate, since comfort constraints are removed (or relaxed) during the evening. Again, off-line studies and on-line adaptive/predictive algorithms can be developed to forecast the charging rate, assuming maximum free cooling will be applied.

The energy stored at the start of occupancy is approximately equal to:

$$Est \approx \sum \rho_i C_{p,i} (\Delta T)_i dV \quad (3-6)$$

where:

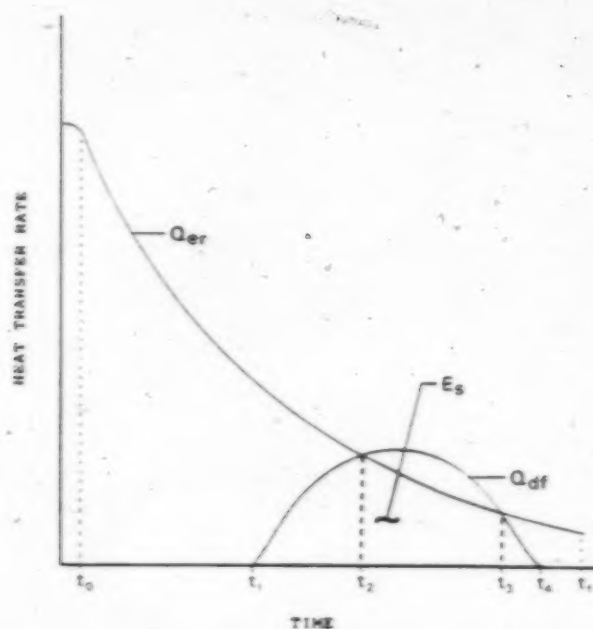


Figure 3.7 Thermal energy storage depletion.

- Est - thermal energy stored within structure
at the beginning of occupancy,
- ρ_i - density of i-th mass element,
- Cp_i - specific heat of i-th mass element,
- dV - elemental volume, and
- (ΔT) - temperature difference between each mass
element and the mean zone air temperature.

However, Est does not necessarily equal the thermal energy *charged* into the structure before occupancy. This is because the mass of a building will likely have retained unwanted thermal energy from the previous day. Therefore, the HVAC system must remove this unwanted energy and charge the structure to the desired value of Est.

Optimum charging. The amount of thermal energy to be charged should minimize the total predicted HVAC energy for the day. This total energy is equal to:

$$E_{tot} = E_{pd} + E_{od} + E_{th} \quad (3-7)$$

where:

E_{tot} - total HVAC energy (for preoccupancy and occupancy operations) for a given day,

E_{pd} - (electrical) preoccupancy distribution energy,

E_{od} - (electrical) occupancy distribution energy, and

E_{th} - thermal energy used (during occupancy).

To minimize E_{tot} with respect to E_{ch} , the thermal energy to be charged into the structure, Equation (3-7) can be differentiated and set to zero. Recognizing that E_{od} is not a function of E_{ch} , the following relationship can be derived:

$$-d(E_{th})/d(E_{ch}) = d(E_{pd})/d(E_{ch}) \quad (3-8)$$

E_{th} can be related to E_s as follows:

$$E_{th} = E_{th_0} - E_s \quad (3-9)$$

where E_{th_0} is the thermal energy spent when $E_{ch} = 0$.

Therefore, Equation (3-8) can be rewritten as:

$$d(E_s)/d(E_{ch}) = d(E_{pd})/d(E_{ch}) \quad (3-10)$$

The significance of Equation (3-10) is shown in Figure 3.8. The total HVAC energy used in a given day will be minimized when the slopes of E_{pd} and E_s are equal (provided $E_s > E_{pd}$). Beyond this point, additional charging will require more distribution energy than the corresponding increase in E_s . For certain conditions, E_{pd} may always be greater than E_s . In other words, the energy used before occupancy will always be larger than the thermal energy saved. In this case, E_{tot} will be a minimum with no precooling/preheating applied.

The aforementioned theoretical development is intended to help determine what time an HVAC system should be turned on. If precooling or preheating will not save energy, an air system should be started at the latest possible moment. However, when preoccupancy thermal manipulation will save energy, the HVAC system should be initiated at the time which minimizes E_{tot} .

To apply preoccupancy thermal inertial control to real HVAC systems, it is necessary to (1) develop algorithms for the energy management system, and (2) run the computer program on-line. The development of preoccupancy algorithms can be built upon the theory outlined above. The general procedure is summarized in Figure 3.9. (See also Section 4.2.3 for the specific preoccupancy algorithm developed for the pilot study.)

For on-line use, preoccupancy computations require real-time state variable inputs. State variables required

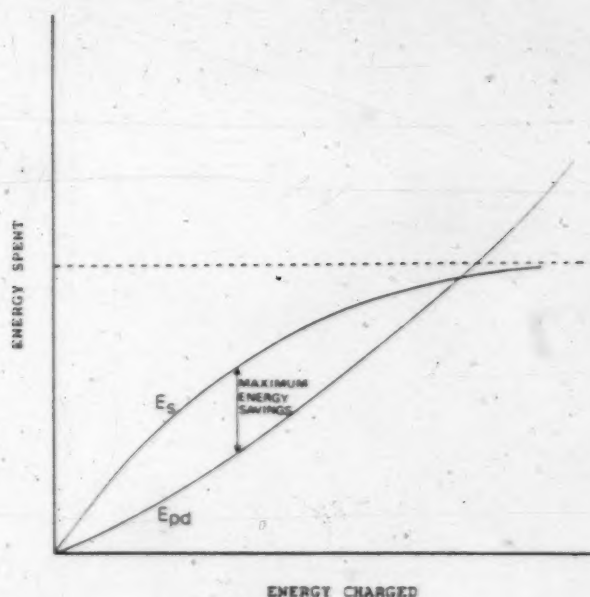
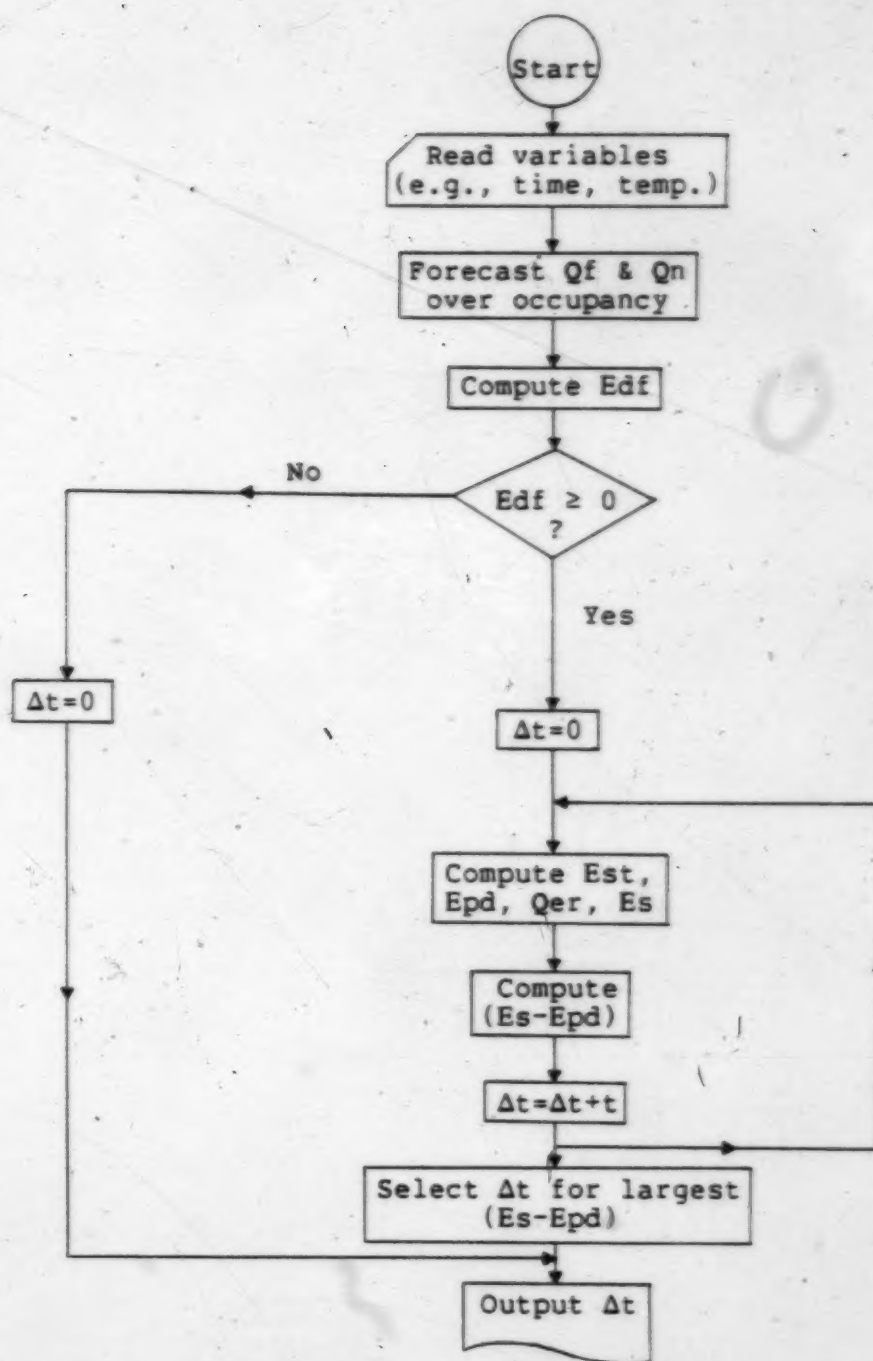


Figure 3.8 Typical energy savings with preoccupancy thermal charging.

for forecasting Q_n and Q_f are discussed in Section 3.2.3. In addition to these rates, dynamic control requires some measure of the thermal energy stored within the building. Without this indicator, Q_{er} , E_{ch} , E_{st} , and E_s would be difficult to determine.

Normally, space temperatures, pressures, and humidity are the only variables monitored (outside of the conditioning system). Since none of these variables directly indicate the quantity of energy stored within the structure, it is suggested that a new variable be monitored. Energy storage within thermal reservoirs is determined by temperature measurements of the storage medium. It follows that the thermal storage in an entire structure can be estimated from one or more temperature measurements of

**Notes:**

Δt = preoccupation operation

t = unit time interval

Figure 3.9 Flow chart illustrating the determination of preoccupation duration.

certain mass elements. For example, if the majority of thermal energy is stored within the floors of a building, a temperature sensing device could be embedded into a floor at a representative spot.

The on-line estimation of thermal storage and release is helpful not only to preoccupancy computations, but also to occupancy control, since thermal inertia can be controlled during both periods to save energy.

3.2.2 Application to Daytime Control

Thermal inertia (and its effects) exist within buildings at all times. However, there are only two operating periods when a structure can be thermally manipulated, namely--preoccupancy control and daytime control. The other periods (i.e., warmup, shutdown,¹⁴ and off), though affected by thermal inertia, cannot have the mass of the building thermally manipulated.

Daytime operation can use the effects of thermal inertia to save energy whenever the outdoor air is within the balance temperature range during the majority of operation. Hartman (1980) explains that:

To do this, a dynamic control system...either acts to capture or to flush out heat generated by internal sources during that portion of the day when the outside temperature is within the balance

¹⁴ Warmup and shutdown algorithms are discussed under Section 3.3.

temperature range.

(Page 1)

In this manner, the resulting thermal flywheel effect will enable the HVAC system to employ free cooling when heating or cooling would normally be required.

The essential principles governing daytime thermal manipulation are similar to those outlined under Preoccupancy Operation. Both applications use free cooling to manipulate the thermal mass, and require a limited knowledge of future occurrences. As well, both schemes are intended to reduce daytime thermal energy consumption. However, they differ in terms of the time frame involved and the required comfort constraints. Whereas preoccupancy algorithms require predictions up to several hours from real time, daytime inertial control is only concerned about occurrences a few hours into the future. Likewise, preoccupancy comfort constraints are not as severe as daytime requirements, since few occupants will be present before normal operating hours.

The strategy development which follows will review pertinent theory, propose solutions, develop a general algorithm, and discuss the practical aspects of implementation.

When the outdoor air is forecasted to exceed the EBTR, thermal energy can be stored beforehand. To carry out this dynamic strategy, it is necessary to answer the following

questions:

1. At what real time will the EBTR be exceeded?
2. How much thermal energy should be stored?
3. When should thermal storage commence?

Answers to these questions require knowledge of the interior temperature, thermal load, rate of heat removal, and time. ASHRAE (1981) has proposed the following room transfer function to approximate the relationship between these variables:

$$\sum p_i (Q_{ac(i)} - Q_{n(i)}) = \sum g_i (T_a' - T_{a(i)}) \quad (3-11)$$

where:

- p, g - room transfer coefficients,
- T_a' - assumed constant space temperature, °C,
- T_a - actual space temperature, °C,
- t - real time, and
- i - summation counter, equal to one hour.

Equation (3-11) can be simplified to obtain an approximate expression for Q_{ac} , Q_n , T_a , and t . Given that¹³

$$T_a = (1/g_o)(I_1 - Q_{ac}, -17.77) \quad (3-12)$$

where: -17.77 = equivalent Celsius temperature for 0°F ,

$$I_1 = T_a' \sum g_i - \sum g_i [T_{a(i)} + 17.77] + \sum p_i [Q_{n(i)}] - \sum p_i [Q_{ac,i}] \quad (3-13)$$

¹³ Equations (3-11) through (3-12) are from ASHRAE (1981).

and defining $\alpha = Ta'(\Sigma g_i)/g_o$, $\beta_i = g_i/g_o$, $\gamma_i = p_i/p_o$, $\bar{T}_a = (T_a + 17.77)$, and $Q_d = (Q_n - Q_{ac})$, Equation (3-11) can be rewritten in vector notation:

$$\bar{T}_a = \alpha - \{\beta\}^T \{\bar{T}_a\} + \{\gamma\}^T \{Q_d\} \quad (3-14)$$

where:

- $\{\beta\}^T$ - (nx1) row vector,
- $\{\bar{T}_a\}$ - (1xn) column vector,
- $\{\gamma\}^T$ - (mx1) row vector, and
- $\{Q_d\}$ - (1xm) column vector.

Equation (3-14) indicates that the room air temperature at time, t , can be estimated by a time series expression of $\bar{T}_a$ and Q_d . In this manner, it is possible to estimate when space temperatures will drift beyond comfort limits (i.e., at what time the EBTR will be exceeded).

If a space temperature is predicted to exceed comfort limits, thermal energy can be stored by altering the space temperature set point. In theory, the duration of this thermal storage should be a function of the severity of the predicted temperature rise/fall. In addition, the interior environmental temperature must not go outside specified bounds or change at a specified maximum rate. Both of these factors can be studied off-line.

The above theory, once analyzed off-line, can be translated into algorithms for on-line operation. An outline of a proposed daytime inertial algorithm is

presented in Figure 3.10⁴.

In practice, the size of vectors $\{Ta\}$ and $\{Qd\}$ in Equation (3-14) should be as small as possible, so that the number of coefficients in $\{\beta\}^T$ and $\{\gamma\}^T$ are minimized. Climatic and occupancy patterns may permit the use of a single time interval for daytime precooling/preheating under all circumstances, thereby reducing the complexity of computations.

3.2.3 Thermal Predictions

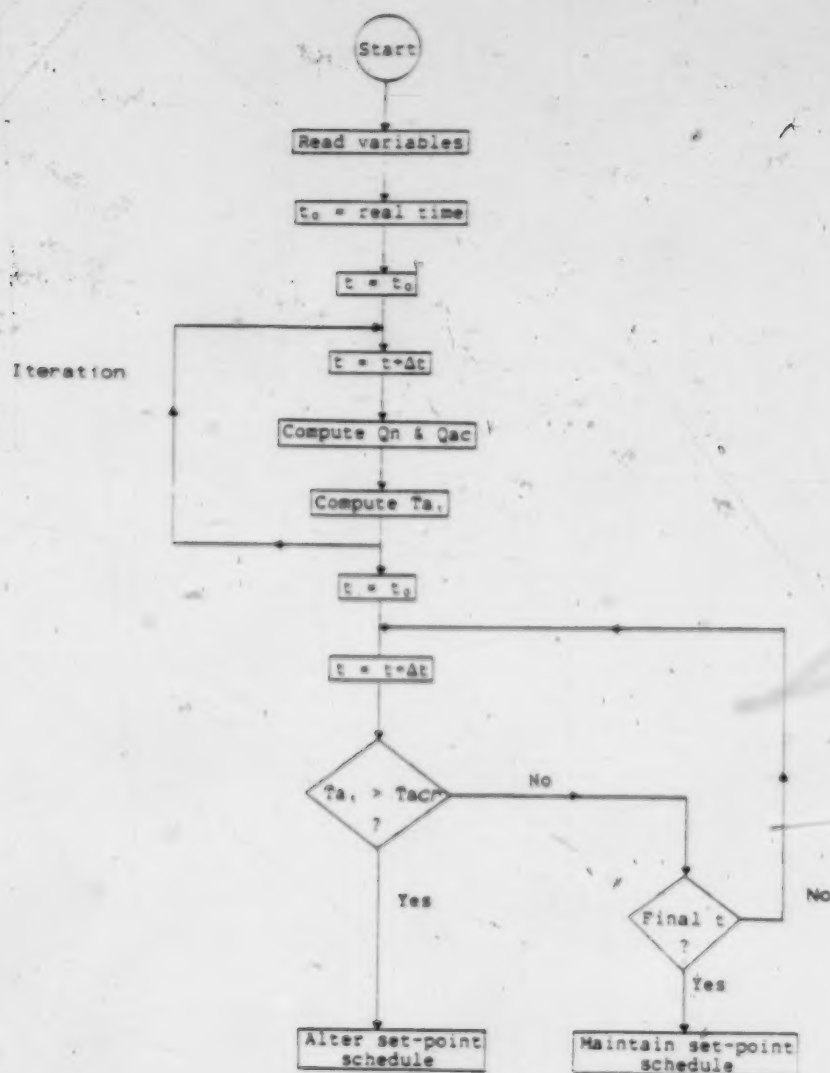
The preceeding sections developed preoccupancy and daytime algorithms assuming that forecasts of the thermal load and system free-cooling capacity were available. This section will discuss how both of these variables (Q_n and Q_f) can be predicted on-line.

Building thermal load prediction¹¹ has been discussed extensively in the literature¹². However, such thermal load calculations have primarily been used to estimate the energy requirements and fuel consumption of HVAC systems. That is, the majority of analysis techniques have been developed for the design process, rather than for in-place control strategies. Energy estimating programs:

1. can be very complex,
2. require large computers and high processing time,

¹¹ Detailed algorithms for the pilot study are given in Section 4.2.3.

¹² See, for example, Hittle (1983), Muncey (1979), and Gupta (1971).



Notes:

t_0 = real time
 t = forecasted time
 Δt = unit time interval
 T_{acr} = critical value of T_a

Figure 3.10 Flow chart illustrating the determination of daytime thermal manipulation.

3. are concerned with large time periods, and
4. are generally run a few times for a given building.

In contrast, load prediction programs developed for dynamic control systems:

1. are restrained in complexity due to limited computing power,
2. are supported by an *on-line* intelligence system,
3. forecast over short time intervals (i.e., less than 24 hours), and
4. are scheduled to run several times each day.

Given the differences between energy estimating programs and the desired dynamic control program, this section will develop algorithms using the following procedure:

1. Review the principles and theories associated with prediction control.
2. Discuss the alternatives available for forecasting Q_n .
3. Discuss the prediction of Q_f .

General Forecasting Theory

The basic problem facing all forecasters is the transformation of past information into future projections. This transformation process is known as time series analysis. The mathematical theories used in forecasting are generally classified as deterministic, stochastic, or both. If a process can be completely defined by some physical law with respect to time, it is deterministic. On the other hand, a completely undefined process is termed as

7

stochastic. There are also certain time series where some of the factors are understood, but there still remains some uncertainty about the future expected value. These would be described as "deterministic plus stochastic". Building load calculations fall into this latter category.

A number of approaches to solving deterministic plus stochastic problems can be taken. Kline (1979), for example, has shown how deterministic and stochastic models can be integrated. Energy estimating programs, however, usually employ only deterministic models, and accept the error incurred by ignoring any stochastic nature in the variables. A third approach to the deterministic plus stochastic problem is an adaptive control model, which has several desirable features, including minimal computing time requirements and acceptable accuracy. Adaptive algorithms do not require detailed knowledge of a building's material properties, or relevant heat and mass transfer characteristics. Their only limitation is their requirement of historical data for model development (which is not always available).

In order to use prediction control, the following factors must be predetermined¹:

1. Object of prediction.
2. Inputs for prediction.
3. Range of prediction.
4. Time of prediction.

¹ Proposed by Kimura (1977).

5. Accuracy of prediction.

The concern of this section is the prediction of building thermal load and system free-cooling capacity over a 24 hour period from real time. However, neither of these parameters can be directly measured. To overcome this problem, measurable variables which affect these heat transfer rates can be used for predictions.

The accuracy of such predictions will depend on:

1. the number of variables considered, and
2. the information available on how these variables affect the parameter of concern.

The information on variable-parameter interaction (e.g., solar radiation-thermal load) is commonly available in two forms: either as records of past operating experience, or as heat transfer models. The simulation programs discussed in the literature (see, for example, Brown, 1971) have been developed almost completely from heat transfer models. However, ASHRAE (1981) has noted that when records of past operating experience are available, they can be used to reliably and accurately predict future energy requirements.

The prediction models discussed on the following pages have been separated into two scenarios: (1) model development with the availability of historical data, and (2) development without historical data.

Thermal Load Prediction (Q_n)

The first step in developing a prediction model is to determine which variables should be considered. Candidate variables which can be easily measured or calculated are listed in Table 3.3. Because each building has unique patterns and structural and material composition, appropriate variables cannot be generalized. Instead, a variable correlation matrix, as described by Forrester and Wepfer (1984), should be used for each building.

Once a signal set (of inputs) has been chosen, an estimate of the future state vector, $\{Q_n\}$, can be generated. This is often accomplished by a regression model, expressing measureable variables (e.g., climate) and unmeasureable variables (e.g., energy stored in the building) in matrix notation. The general form for estimating components of vector $\{Q_n\}$ at time, t , would be:

$$Q_n = a + \sum_{i=1}^n \beta_i x_i \quad (3-15)$$

where:

- a, β_i - regression coefficients,
- x_i - independent variables, and
- n - total number of regressors in the model.

One major difficulty arises from this regressive technique: Q_n cannot be directly measured. The only means of determining Q_n is through detailed heat transfer calculations. Therefore, coefficients a & β_i must be determined through statistical analysis of historical data,

Table 3.3 Variables for load prediction.

Environmental	Outdoor dry-bulb temperature Relative humidity Solar radiation Wind speed and direction.
Interior	Lighting schedules. Equipment schedules Occupancy patterns Interior temperature Interior humidity Interior mass temperature
Control	Supply air enthalpy Supply air flow rate Perimeter radiation temperature Perimeter radiation flow rate

coupled with estimates of Q_n through simulation studies.

When coefficients α & β , cannot be determined due to the absence of historical data, each input (x_i) can be individually forecasted over the desired time frame. The value of Q_n , could then be taken as the algebraic sum of the contributions from each input (Fisk, 1981). This technique is shown in Figure 3.11. The number of variables and the size of the corresponding vectors will depend on the accuracy desired, the significance of each variable, and the type of transfer function used.

The state variables and heat gain/load transfer functions proposed by ASHRAE (1981) for calculating the air-conditioning cooling load are shown in Figure 3.12. Unfortunately, this procedure is too complex for on-line

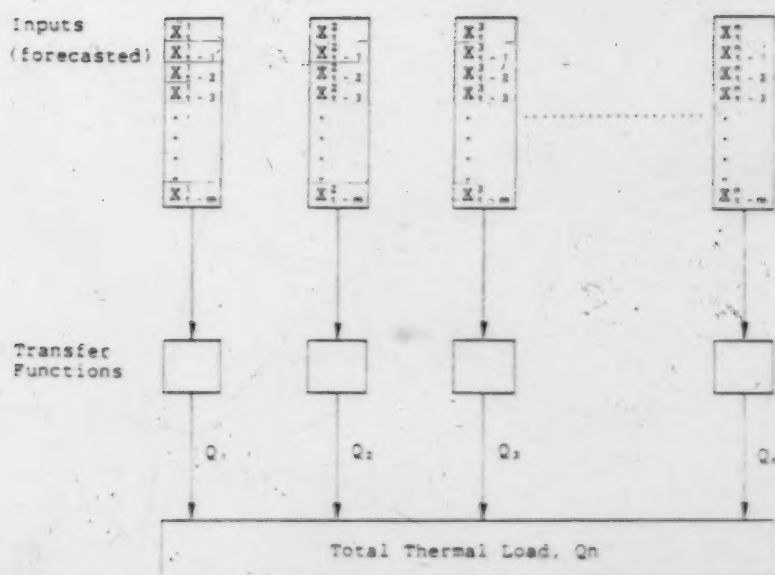


Figure 3.11 Forecasting in the absence of historical data.

computation. Generally, an order of magnitude analysis will show wind speed and direction to be the least significant factors in forecasting Q_n . Therefore, the most realistically involved procedure for on-line prediction of Q_n would use forecasts of solar radiation, outdoor temperature, and internal loads. Techniques for predicting each of these variables is briefly discussed below.

Forecasting solar radiation. The intensity of solar radiation on a building surface is a function of: (1) time, (2) cloud cover, (3) ambient humidity, (4) ground surface reflectance, and (5) orientation of the surface. Horizontal surface ("global") radiation can be broken down into direct and diffuse components:

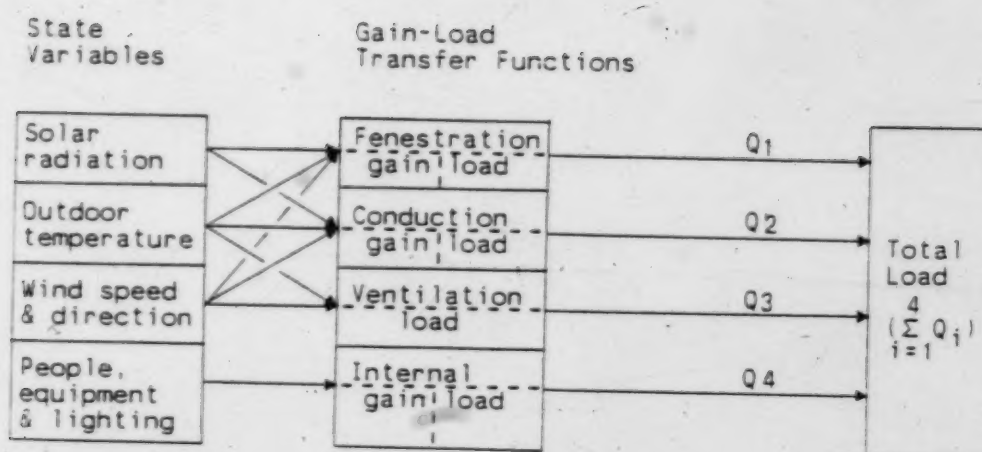


Figure 3.12 Flow diagram for cooling load calculation.

$$I_t = I_{dn}(\cos \epsilon) + I_{ds} \quad (3-16)$$

where:

- I_t - total radiation,
- I_{dn} - direct normal radiation,
- I_{ds} - diffuse radiation, and
- ϵ - solar altitude.

Solar intensity can be predicted under two situations:

- (1) where real-time measurements are available, and (2)
- where active data is not available.

Real-time data can be used to compare actual radiation values with calculated clear sky conditions. Because clear sky radiation values are deterministic, they can be accurately predicted (for any hour of the year) through

standard formulae. Therefore, if the ratio of actual to clear sky radiation is assumed to remain constant (implying a constant cloud cover), forecasts of actual radiation can be made.

When real-time measurements are absent, a deterministic model may be developed, assuming solar intensity to be only a function of time. Radiation records could be analyzed by fast Fourier series, as documented by Hittle (1983). A sinusoidal equation of several harmonics could then be developed, having the form:

$$\begin{aligned}
 I_{x_t} \cong & a_0 + 2[a_1 \cos(2\pi t/8760) + b_1 \sin(2\pi t/8760)] \\
 & + 2[a_{365} \cos(2\pi 365t/8760) + b_{365} \sin(2\pi 365t/8760)] \\
 & + 2[a_{730} \cos(2\pi 730t/8760) + b_{730} \sin(2\pi 730t/8760)] \\
 & + [\text{other harmonics}] \quad (3-17)
 \end{aligned}$$

where:

- I_{x_t} - estimated value of radiation variable,
- a_0 - mean of the radiation variable,
- a_1, b_1 - annual cycle Fourier coefficients,
- a_{365}, b_{365} - daily cycle Fourier coefficients, and
- a_{730}, b_{730} - half-daily cycle Fourier coefficients.

Forecasting outdoor temperature. Short term projections of dry-bulb and/or wet-bulb temperatures can be obtained from:

1. on-site forecasts,
2. off-site forecasts, or
3. combining on-site and off-site forecasts.

When on-site predictions are desired, a deterministic plus stochastic model can be used, based on the following equation suggested by Hittle (1983):

$$\begin{aligned}
 T_t \cong & a_0 + 2[a_1 \cos(2\pi t/8760) + b_1 \sin(2\pi t/8760)] \\
 & + 2[a_{365} \cos(2\pi 365t/8760) + b_{365} \sin(2\pi 365t/8760)] \\
 & + 2[a_{730} \cos(2\pi 730t/8760) + b_{730} \sin(2\pi 730t/8760)] \\
 & + \phi_1 T_{(t-1)} + \phi_2 T_{(t-2)} \quad (3-18)
 \end{aligned}$$

where:

- T_t - estimated value of the future temperature at time t ,
- a_0 - annual mean temperature,
- ϕ_1, ϕ_2 - constant autoregressive model parameters, and
- $T_{(t-1)}, T_{(t-2)}$ - values of temperature at times $t-1$, $t-2$.

The determination of Fourier coefficients and autoregressive parameters necessitates the availability of historical data. After these coefficients have been determined, real-time measurements are fed into the model to forecast T_t .

On-site forecasting models are limited to knowledge of present and past temperatures. Regional forecasts, however, are able to study a number of factors such as cloud cover and wind velocity. Logically, these forecasts should be more accurate. This unfortunately is not true for short-term forecasts (i.e., up to six hours from real time), because of the time lag between data measurements and

forecasts.

The advantages and disadvantages of both on-site and off-site temperature forecasts are listed in Table 3.4. Off-site forecasting should be limited to temperature predictions beyond six hours from real time, or used to subjectively check on-site predictions.

Predicting internal cooling loads. Internal heat gains (and their resulting cooling loads) originate from three sources:

1. people,
2. lighting, and
3. equipment.

Fortunately, most commercial and institutional buildings experience the same internal load profiles each day. That is, heat emanating from the aforementioned sources is only a function of time-of-day. Therefore, once daily profiles have been determined, the total internal load for any hour need only be calculated (off-line) once.

System Free-Cooling Capacity Prediction (Q_f)

As suggested by ASHRAE (1981), the cooling heat transfer rate supplied to a zone is approximately¹ equal to²:

$$Q_{ac} \cong \eta v \Delta T \quad (3-19)$$

¹ Latent heat gains have been ignored.

² Equation (3-19) is taken from Equation 24 in Chapter 26 of ASHRAE (1981).

Table 3.4 On-site and off-site forecasting.

Forecast	Advantages	Disadvantages
On-Site	1. Most accurate for short-term forecasts. 2. Completely automatic. No operator intervention. 3. Can be continuously updated. 4. Provides hour-by-hour prediction.	1. Requires mathematical and statistical modeling. 2. Less accurate for long range (6 hrs. +) forecasts. 3. Cannot predict drastic weather changes.
Off-Site	1. Requires no data analysis. 2. Most accurate for long term (6 hrs. +) forecasts. 3. May anticipate drastic weather changes.	1. Less accurate for short-term forecasts. 2. Only provides max/min. predicted temperatures. 3. Forecasts only available once every 12 hours. 4. Requires operator intervention.

where:

η - proportionality constant,

v - air delivery flow rate,

ΔT - difference in dry-bulb temperature of incoming air and leaving air.

Under free-cooling, v can be easily calculated from fan data or measured. As well, the temperature difference, ΔT , under maximum free-cooling (ΔT_f), will equal:

$$\Delta T_f = T_a - T_o - \Delta T_d$$

where:

T_a - mean space temperature,

T_o - outdoor temperature, and

ΔT_d - temperature rise of outdoor air

across supply fan(s).

Therefore:

$$Q_f \approx \eta v [T_a - T_o - \Delta T_d] \quad (3-20)$$

An order of magnitude analysis will indicate that T_a and ΔT_d variation with time is insignificant compared to T_o . Therefore, Q_f can be predicted using T_o as the only state variable.

The accuracy of thermal predictions will largely depend on the sophistication of computations and the quantity of measurable data. It is therefore essential to develop models with an understanding of the limitations and characteristics of current HVAC control systems.

3.2.4 Use of Central Control Systems

The prediction and decision making algorithms required for dynamic control necessitate intelligent control systems. These systems are commonly referred to as central monitoring and control systems (CMCS), remote control and monitoring systems (RCMS), energy management systems, or intelligent control systems. This section is intended to develop the necessary understanding for effectively implementing the dynamic control strategy developed in this study. Both state-of-the-art hardware and software systems will be discussed, followed by a discussion on how these items can affect the development and performance of a dynamic control

system.

Early intelligent control systems used a "monolithic home-run" system, with all components (e.g., sensors, actuators, etc.) wired directly to the central processor (Ranieri, 1982). With the advent of the microprocessor, implementation of various functions can now be done at a number of locations. This "distributed hierarchy" is appealing, since "intelligence" does not reside at a single vulnerable point.

A hierarchical control system uses a series of loops, with mechanical equipment control at the innermost loop. A second level of control both monitors the first level, and sends it command signals. High-level decisions (e.g., optimization programs) are performed at a third level (i.e., "outer loop"). A typical distributed system is shown in Figure 3.13.

Level one of a CMCS usually possesses little or no intelligence; it waits for commands from the next higher level to either send data or to exert one control transaction. This first level typically has a fixed program written in machine language and is therefore not end-user programmable.

Level two is aware of the "should be" status of machinery, and, occasionally, the time-of-day. When the next higher level is off-line, the second level has some default program which permits continued operation of the building.

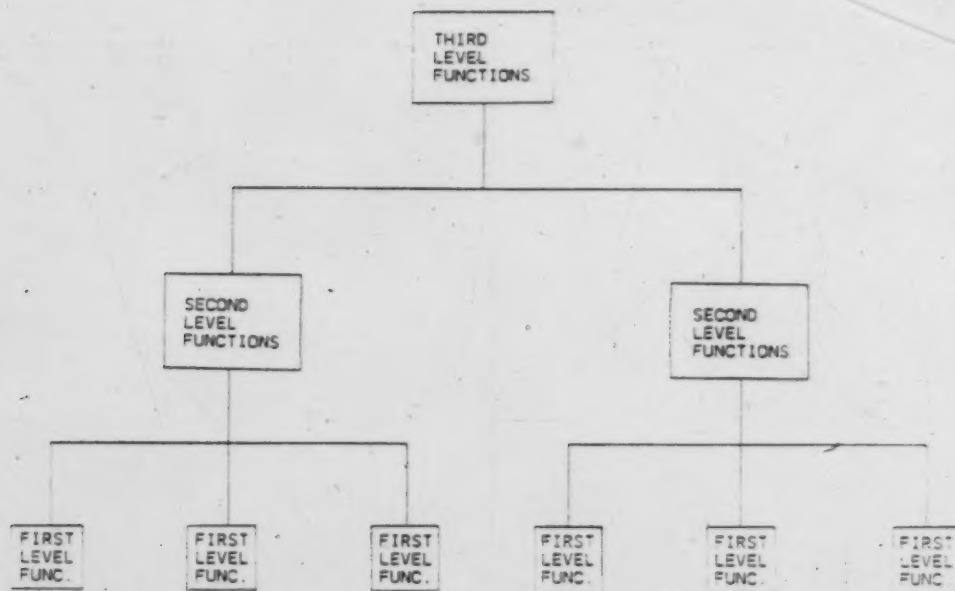


Figure 3.13 Distributed processing architecture.

The third level is a computer mainframe, often called the "executive" (or "host"). Its primary functions include operator interface, data acquisition, energy management, and fire and security.

For each level of control hardware, there must be software to initiate any task. For example, the real-time executive³¹ performs high-level tasks, such as start/stop functions, trending, and predictive control. Level two might include software for control of outside air intake, perimeter radiation valve positioning, et cetera.

To integrate the algorithms discussed in this chapter with the computer framework, it is important to consider the following characteristics:

1. The degree of algorithm sophistication.

³¹ Also known as system software.

2. The required frequency of computations.
3. The appropriate CMCS level for software, such as:
 - a. real time,
 - b. data base, and
 - c. calculations.

The complexity of any algorithm will be constrained by the overall computing power of the CMCS and the frequency at which the algorithm must be run. Computational tasks which are required in the order of one run per minute should be executable in the order of one second. Conversely, sophisticated algorithms requiring in the order of one minute running time shouldn't be performed more than once per half hour. Preoccupancy and daytime algorithms would fall under this latter category.

It is important to select the appropriate level(s) of CMCS hierarchy for dynamic control tasks. Sophisticated routines such as data storage and complex mathematics (e.g., trigonometry and matrix operations) usually can only be performed by the executive. However, less sophisticated routines (such as free-cooling operation) should be placed at lower CMCS levels to avoid loss of communication during executive break down.

In summary, dynamic control algorithms must be developed in light of the available computing power and the CMCS level at which they will operate under.

3.3 Interior Temperature Drifting

Whereas the traditional control design process attempted to create systems which maintain a specified set point, dynamic control design focuses on energy efficiency. This means a comfort range can be established which will permit interior temperature drifting, thereby reducing energy consumption by:

1. extending the effective balance temperature range of a system, and
2. allowing thermal manipulation of the building.

To develop a strategy which utilizes temperature drifting most effectively, the general concepts of thermal comfort will be explored, followed by algorithm development for both warmup and shutdown periods.

3.3.1 Theory

As noted in Chapter 2, accompanying this study's objective of energy reduction are two comfort constraints: a maximum temperature drift rate, and maximum/minimum comfort bounds. The critical temperature drift rate of 0.75°C/h applies at all times during occupancy, but not at all during unoccupied periods. In contrast, comfort bounds need not remain constant during occupancy, as they are known to be zone-dependent and time-dependent.

Temperature bounds chosen for normal operating hours will be a function of the nature of work being performed in the zone. For example, computing facilities may require

bounds different than those for business offices.

Although a building population will demand some minimum level of comfort during the day, temperature comfort bounds may be enlarged at the beginning and end of occupancy. During these periods, occupants are either anticipating impending comfort enhancement, or preparing to leave. This is shown in Figure 3.14.

Recognizing these dynamic comfort constraints, it is appropriate to integrate temperature criteria with overall operating strategy.

3.3.2 Application to Warmup Control

Warmup control is the term applied to the operation period just before the start of occupancy. It is sandwiched in time between preoccupancy operation and daytime operation. The purpose of this control mode is to ensure that impending occupancy comfort constraints will be met. To guarantee minimum energy use, its period of operation should be as short as possible.

Warmup algorithms discussed in the literature simply determine the optimum run time. Kamimura (1982) has suggested this can be estimated as follows:

$$t_w = (\theta_d - \theta_i) / K \quad (3-21)$$

where:

t_w - duration of warmup period,

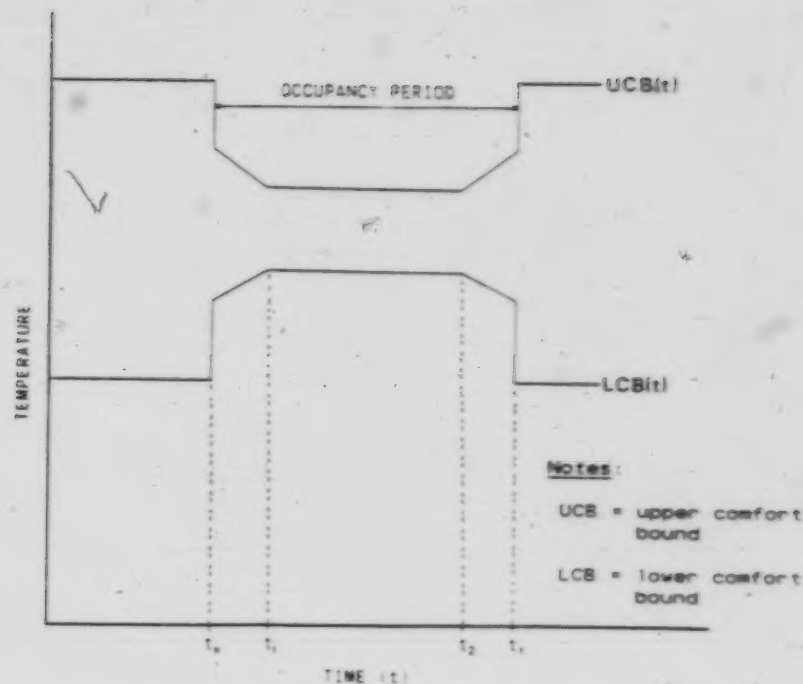


Figure 3.14 Time-dependent comfort bounds.

- θ_r - desired resultant temperature,
 θ_i - initial resultant temperature, and
 K - room temperature drift rate.

The room temperature drift rate is a complex function of outdoor temperature, wall surface temperature, heat storage in the air-handling unit, solar radiation, et cetera. Instead of accounting for all these variables, Kamimura has proposed an adaptive approach, using historical data; that is:

$$R_{(i+1)} = (1-s)R_{(i)} + sR \quad (3-22)$$

where:

- $R_{(i+1)}$ - estimated room temperature drift rate for (i+1)th day,
- $R_{(i)}$ - measured room temperature drift rate for (i)th day,
- R - moving average room temperature drift rate over several days, and
- s - weighting factor ($0 \leq s \leq 1$)

If this algorithm is to be used in conjunction with the dynamic comfort bounds shown in Figure 3.14, it is important to realize that, starting from time, t_0 , the heat generated from people entering the building, turning on lights, et cetera, will tend to increase the space temperature. Therefore, in the case of θ_s being above or below daytime comfort bound values, the value of θ_s should take into account this "natural" temperature rise from the entry of people. This consideration, coupled with the algorithm of Kamimura (1982) is shown in Figure 3.15.

It should be noted that the duration of warmup cycle is normally much shorter than the time constant²² of the building. Therefore, if a building were first precooled, the warmup cycle would not greatly alter the building mass temperature by the start of occupancy. Instead, θ_s would be largely achieved through an increase in T_a , the room air temperature. In this manner, the cooled mass can absorb

²² Time constant in this study means the time a process would have needed to reach an ultimate value if the initial rate of heat transfer had been maintained throughout. See Wolsey (1975) for further details.

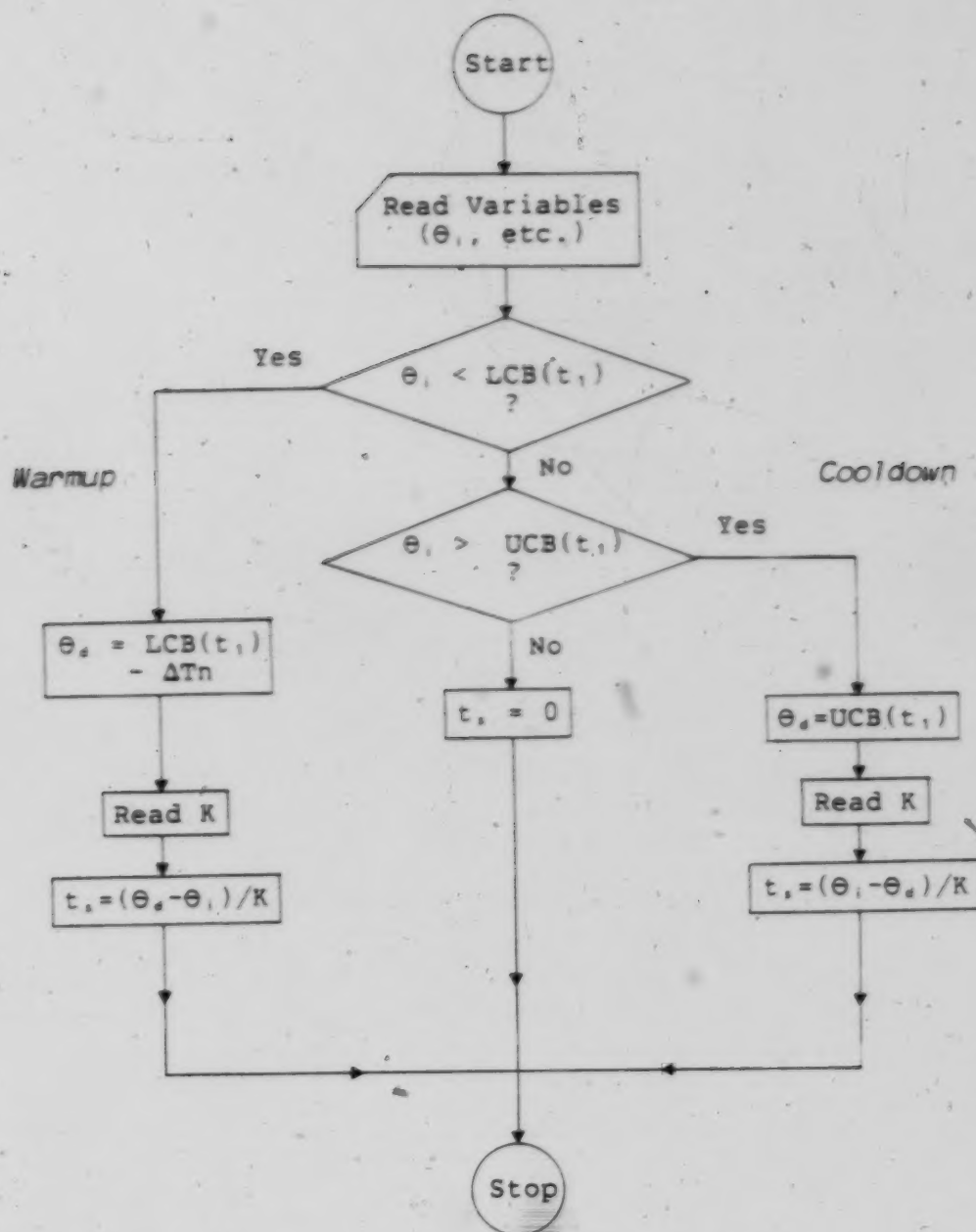


Figure 3.15 Flow chart illustrating the duration of warmup duration.

impending heat loads.

3.3.3 Application to Shutdown Control

Shutdown control calculates the earliest time to stop the air-conditioning system. This will occur some time before the end of occupancy, so that the interior temperature will drift to the (daytime) comfort zone limits just after occupancy. This is shown schematically in Figure 3.16.

The formula proposed by Kamimura (1982) for warmup control can also be applied to optimum stop. The duration for which the air conditioning can be off (before the end of occupancy) is estimated as:

$$t_{s,j} = (-1)^j (\theta_i - \theta_{s,j}) / K' \quad (3-23)$$

where:

- $t_{s,j}$ - duration of shutdown status during occupancy,
- j - $j=1$ for cooling and $j=2$ for heating seasons,
- θ_i - initial (real-time) resultant temperature,
- $\theta_{s,j}$ - target resultant temperature at end of occupancy,
- K' - room temperature drift rate with no air conditioning.

If it is difficult to stop the fans because of ventilation requirements, then this routine can be used to estimate the earliest time to disable heating/cooling coils if they are currently being used. The algorithm would be skipped if free-cooling was already in operation.

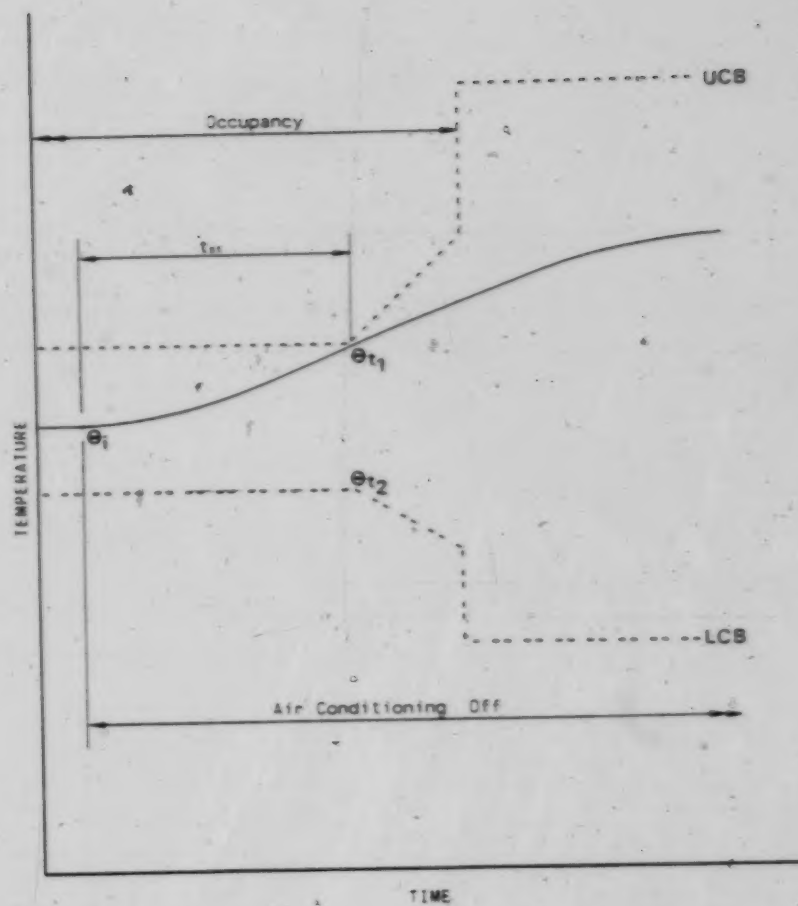


Figure 3.16 Optimum shutdown control.

4. STRATEGY TESTING

To this point, the essential concepts of dynamic control have been reviewed and translated into general algorithms, based on the theory of heat transfer. To gain further insight into the subject of optimal implementation, an existing building was modified according to the strategy developed in the preceeding chapters. By actually installing a dynamic control system, it was hoped that parameters which are not easily quantified in theory (e.g., manpower requirements, occupant acceptability, etc.) could be analyzed through empiricism. Moreover, a case study can aid identification of typical procedures necessary in translating generalized schemes into algorithms specific to a particular building.

This chapter outlines the conditions of the pilot building and its HVAC system before implementation of the project. Next, the changes made to create a dynamic control system are documented. Finally, the chapter describes the testing procedures employed to evaluate the implementation performed.

4.1 The Administration Building

The building chosen for this study is located on the University of Alberta campus (in Edmonton). Providing office space for various administrative services for the university, the Administration Building's construction was completed in 1956. The exterior design is shown in

Figure 4.1.

Since its opening, a number of changes have been made to its interior design and HVAC system. In 1982, the University's Physical Plant installed a direct digital computer control system in the Administration building, and connected it to the campus' remote control and monitoring system (RCMS). While the Physical Plant was performing various energy conservation measures, offices were being upgraded with new equipment, including a mainframe computer for office work.

The Administration Building was chosen for this study for the following reasons:

1. Load predictability. Internal loads are easily predictable since occupants perform similar tasks each day. Few people work before or after building hours.
2. Geometric simplicity. In terms of thermal analysis, the Administration Building's rectangular shape and symmetry ease any computations.
3. Comfort enhancement. The existing air-conditioning system has a history of not being able to meet cooling loads during hot summer days. It was hoped that the new strategy would improve the system's performance during these periods.
4. Thermal inertia controllability. The thermal mass of the Administration Building is large enough to store a significant amount of heat.

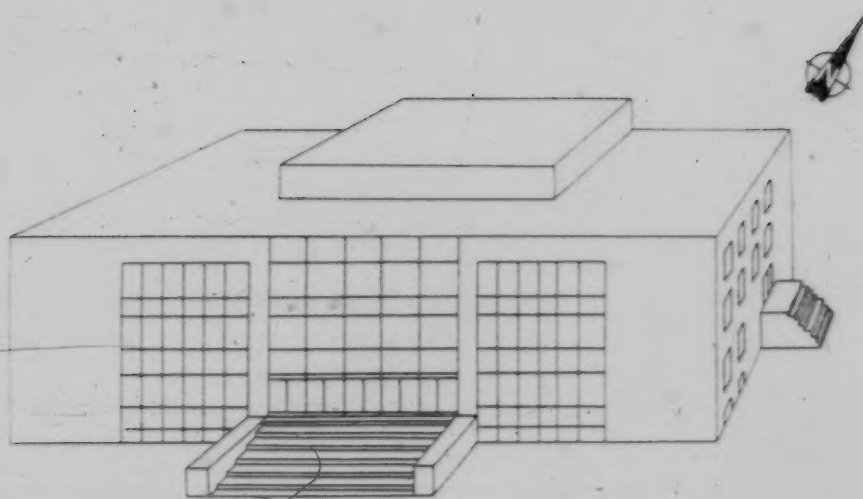


Figure 4.1 Sketch of the pilot building.

4.1.1 Construction, Use, and Systems Profile

Figure 4.2 details the construction and use profiles of the Administration Building. In addition to the basement, there are three floors above grade, plus a penthouse containing the main air-handling unit. The Administration Building has load-bearing brick walls and a built-up roof. The interior has 150 mm concrete floor slabs, false ceilings, and typical office partitions.

Most occupants enter the two main sets of doors at the north and south sides of the building. Visitors are mostly students, and comprise approximately ten percent of the total building population. The other occupants are predominantly sedentary office employees who remain within the building from 8:30 to 16:30, Monday to Friday, excepting lunch hour. Besides general offices, there is one cafeteria, a main reception/information area, a computer

Primary Building Use: Office

Exterior Dimensions:

Dimension	Distance (m)	Orientation
Length	52.0	W-E
Width	20.9	N-S

Floors: S.O.G. and suspended concrete

Level	Gross Area (m ²)
Basement	1168
1st	1085
2nd	1085
3rd	1085
Penthouse	319
Total	4742

Exterior Doors:

Orientation	Type	Number	Gross Area (m ²)
North	single	6	12.4
East	single	2	3.3
South	vestibule	6	12.4
West	single	1	2.1
	freight	1	4.5

Walls:

Location	Description	Orientation	Net Area (m ²)
Basement	concrete c/w insulation & plaster	All	2270
Exterior	brick and clay c/w plaster	North	705
		East	327
		South	705
		West	327

Windows: Double pane, 12.5 mm air space, wood sash; metal clad doors.

Orientation	Net Area (m ²)
North	111.5
East	43.9
South	138.2
West	42.5

Roof: Built-up: 150 mm concrete c/w rigid insulation; areas 1188 m²

Occupants: Number of occupants: 262 during school
242 during summer
No. of work hours/week: 35

Custodians:

Period	Number of Hours per Week	Comments
Total	144	11 p.m. Sunday, to 11 p.m. Friday
After dark	45	summer
Saturdays	70	winter
Sundays	0	
	1	11 p.m. on

Air handling: Current schedule (on): 4 a.m. - 8 p.m. Monday - Friday
Design flow rate: dual duct system: 11400 l/s
a/c cabinets in Room 7: 7400 l/s

Figure 4.2 Construction and Use Profile.

room, and a mechanical and electrical room in the basement. Of great significance for this study is the high population density in the building, resulting in large internal cooling loads.

Figure 4.3 summarizes the electrical and mechanical systems which existed during this pilot project. All lighting within the Administration Building is from 40 Watt fluorescent bulbs, fixed in recessed, unvented fixtures. The electrical system also supplies power to office equipment such as the mainframe computer, computer terminals, typewriters, et cetera, and the HVAC equipment.

Air distribution in the building is mostly provided by one air system, located in the penthouse mechanical room. After a common precooling coil, the system is divided into two zones of medium velocity dual duct runs, as shown in Figure 4.4. The west side of the first floor had been converted to a variable volume system with cold duct supply only. Terminal boxes in this area have a minimum setting of 30 percent of maximum flow capacity. Single-line air schematics, showing the east/west zone divisions and locations of space thermocouples on each floor appear in Appendix A-1.

Additional cooling is provided to the computer room (Room 7) by two air-conditioning cabinets; additional heating is supplied to perimeter zones by the radiation system shown in Figure 4.5. As well, major entrances have unit heaters.

ELECTRICAL LIGHTING SYSTEMS:

Light fixtures in primary spaces (e.g., offices):

Type	Number	Wattage/Fixture	Total kW
2x40w fluorescent	616	80	49.3

Light fixtures in secondary spaces, such as corridors, toilet rooms, storage rooms.

Type	Number	Wattage/Fixture	Total kW
2x40w fluorescent	107	80	8.6

Total installed kW: 57.9

ELECTRICAL OFFICE EQUIPMENT:

Types of equipment:
mainframe computer, computer terminals, photocopiers, typewriters, adding machines.

Approximate average diversity factor:
Monday-Friday, 8:00-17:00 $\approx$ 0.62

VERTICAL TRANSPORTATION:

2 elevators: 1 passenger & 1 freight, both 208 V, 3 phase

DOMESTIC HOT WATER SYSTEMS:

Method of generation and storage:
1 DHW converter, supplied with low pressure steam.

Estimated annual usage:
802 735. l

HVAC SYSTEMS:

All air systems:

Type	Description	Flow rate (l/s)
Single zone	Rm 7 air conditioner #1	2667.
	Rm 7 air conditioner #2	4720.
	Mech rm fan coil unit	826.
Dual duct	Penthouse (main unit)	11449.

Water-air systems:

Unit heaters, total of 9, hot water coils.

Radiation system:

Description: Hot water fin-vectors
Primary locations: perimeter zones

Exhaust fans:

Types: Washroom, storage, and
penthouse.
Total flow rate: 1527. l/s

Pumps:

Type	Number of units	Total connected power (kW)
Chilled water	1	3.7
Steam condensate	2	0.7
Hot water (for space heating)	6	2.2
DHW, recirculating	1	0.2
Sump	1	0.2

Fans:

Type	Number	Total power (kW)	Design flow rate (l/s)
Return	1	9.5	17 500.
Supply, dual duct	1	37.3	11 400.
Supply, supplementary	3	3.4	7 400.
Exhaust	5	2.6	2 100.

Figure 4.3 Electrical and mechanical systems profile.

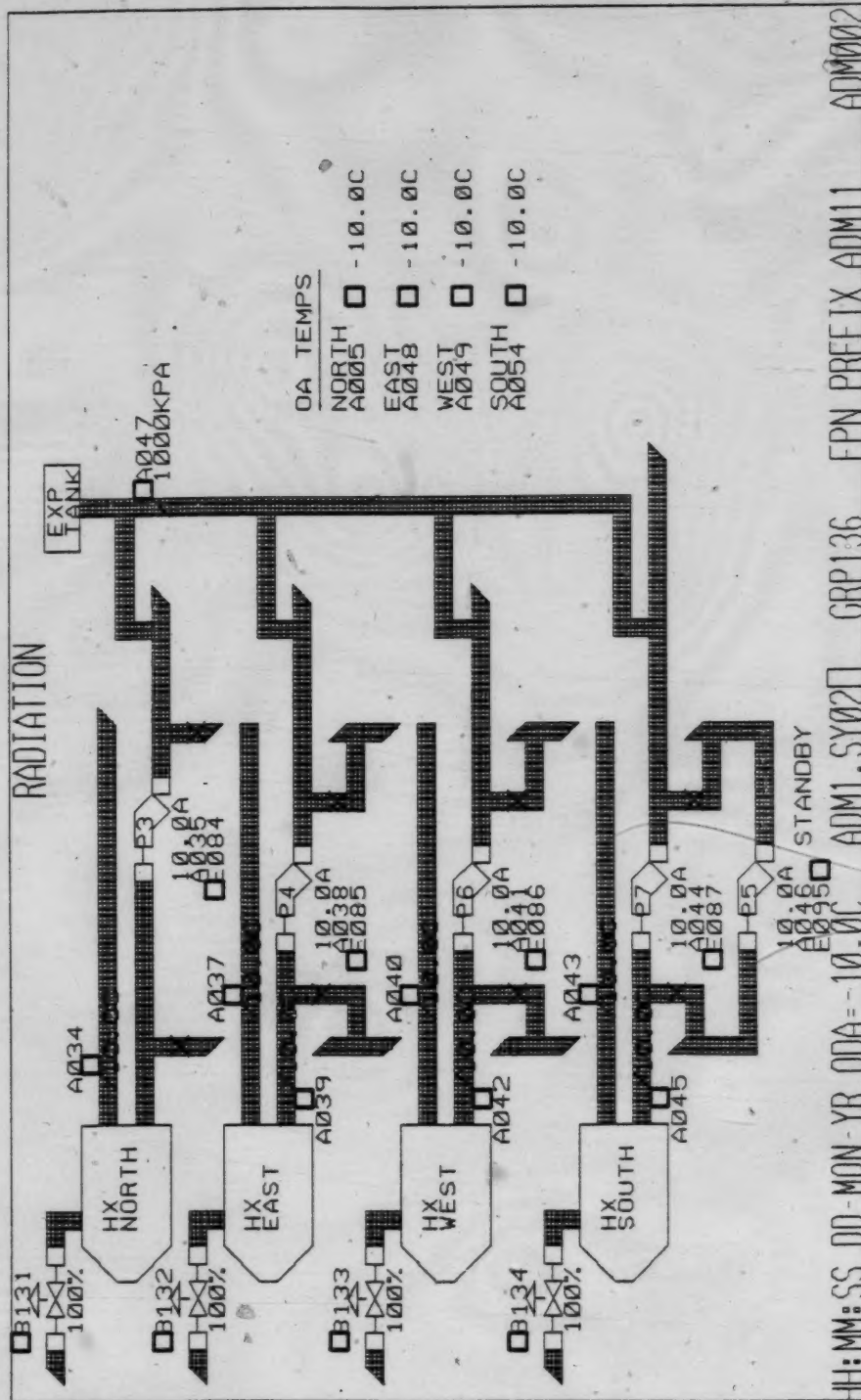


Figure 4.5 Perimeter radiation schematic.

4.1.2 Existing Control

Since the Administration Building is connected to the campus remote control and monitoring system, a number of levels of control exist. A schematic of the RCMS architecture is presented in Figure 4.6. Typical components include:

1. sensors and actuators,
2. interface panels,
3. process control modules, and
4. a central (host) computer.

The process control modules (PCM's) carry out all field control and monitoring functions, and operate totally independent of each other. They consist of a microprocessor complete with processor memory, external signal interfaces, and communications channels connected to the central host computer by cables.

All of the PCM's in the University buildings are linked to a central facility, so that monitoring and control can occur at a single location. A large minicomputer (the host) performs the following functions:

1. Loading PCM data bases.
2. Supporting operator terminals.
3. Supporting graphics terminals.
4. Polling PCM's for alarms.
5. Supporting applications software.

The University also operates another minicomputer for off-line functions, such as software development, data base

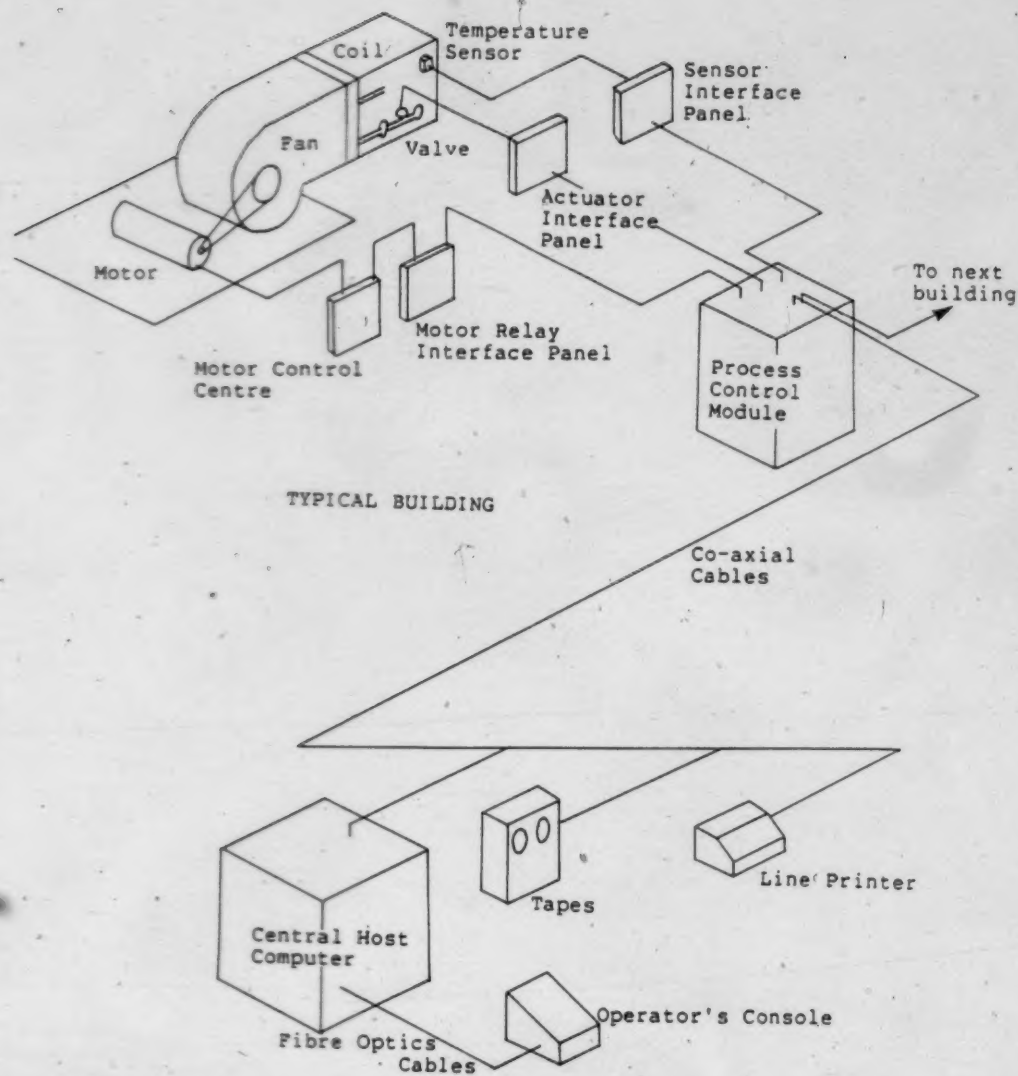


Figure 4.6 The University of Alberta RCMS system.

programming, and documentation.

The software supporting the above hardware is divided into three categories; namely:

1. RSX11/M+, supplied by Digital Equipment,
2. EMCON-D, purchased from SA Engineering Ltd., and
3. University of Alberta applications software.

The RSX11/M+ presently supports* FORTRAN and Macro languages, and acts as a real-time executive. The EMCON-D runs under the RSX11/M+, doing all the basic functions required in a distributed monitoring and control system. For example, scanning at the PCM level, and graphics and communications tasks at the host level are performed. University of Alberta software also runs under the RSX11/M+, carrying out optimization tasks, data logging, report tasks, et cetera. A summary illustration of the software distribution is shown in Figure 4.7.

Within the Administration Building, a PCM controls the central components of the dual duct air-handling system and the perimeter radiation system. Sensors and actuators for these systems, which are connected to the RCMS, are listed in Table 4.1.

Local control is not part of the RCMS. Instead, thermostats control supply air mixing boxes pneumatically. The radiation system is not controlled locally; instead, its operation is scheduled within the PCM.

Just before changes were made to the Administration Building for dynamic operation, the air-handling unit and

Table 4.1 RCMS state variables for the Administration Building.

Main Air-Handling Unit		
Points Controlled	Type	Points Monitored
1. Outdoor air damper	A	1. Outdoor air temperature
2. Return air damper	A	2. Mixed air temperatures (before and after supply fan)
3. Exhaust air damper	A	3. Duct supply temperatures
4. Supply fan	D	4. Cooling coil water temperatures
5. Return fan	D	5. Heating coil water temperatures
6. Cooling coil valves	A	6. Space temperatures
7. Heating coil valves	A	7. Mixed air pressures (before and after supply fan)
8. Steam humidity valve	A	8. Differential pressures between hot and cold decks
9. Chilled water pumps	D	9. Exhaust air pressure
		10. Cold deck relative humidities
		11. Return air relative humidity
		12. Fan amperage
Perimeter Radiation System		
Points Controlled	Type	Points Monitored
1. L.P. steam supply valves	A	1. Outdoor air temperatures
2. Hot water pumps	D	2. Hot water supply temperatures
		3. Hot water return temperatures
		4. Pump amperage

Notes:

A = analog

B = digital

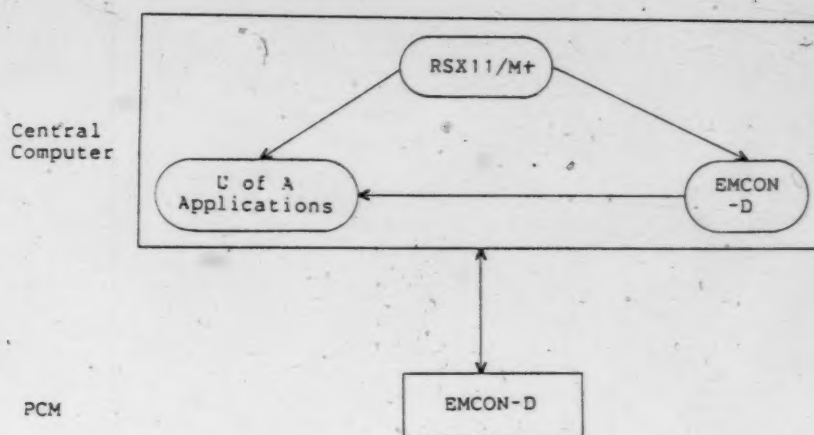


Figure 4.7 RCMS software distribution.

radiation systems were controlled in the following manner:

1. Air-handling unit.

- a. The cold-duct air temperature set point was fixed at 13°C during operation (for both zones). This point modulated the flow rate of the chilled water to the cooling coils.
- b. The cold-duct controller with the higher cooling demand was selected to control the mixed air dampers. Economizer scheduling was used.
- c. The differential pressure between hot and cold ducts controlled the set point for the hot-duct temperature controller. At low differential pressures, the hot duct set point was moved upwards (to a maximum of 40°C); at high differential pressures, the set point was lowered (to a minimum of 20°C).
- d. The return air humidity controlled the humidity valve.

2. Radiation system.

a. The hot water radiation was divided into four control zones--north, west, south, and east. Each zone has its own pump, temperature controller, and outdoor temperature sensor.

b. All four zones had their hot water supply temperatures set from outdoor air temperatures and hot-duct temperature set points. A low-limit schedule was based on the outdoor temperature. The high limit for the radiation set point was 20°C higher than the low limit. Settings between low and high limits were based on selected hot-duct set points. This schedule is summarized in Figure 4.8.

c. Pumps for each zone were scheduled to be on whenever the outdoor temperature was below 10°C.

Other HVAC systems (e.g., unit heaters, air-conditioning cabinets, etc.) were controlled locally. Exhaust fans (except for the main system return fan) were scheduled to remain on continuously.

4.1.3 Historical Energy Use

There are three sources of primary energy used by the Administration Building; namely:

1. steam,
2. chilled water, and
3. electricity.

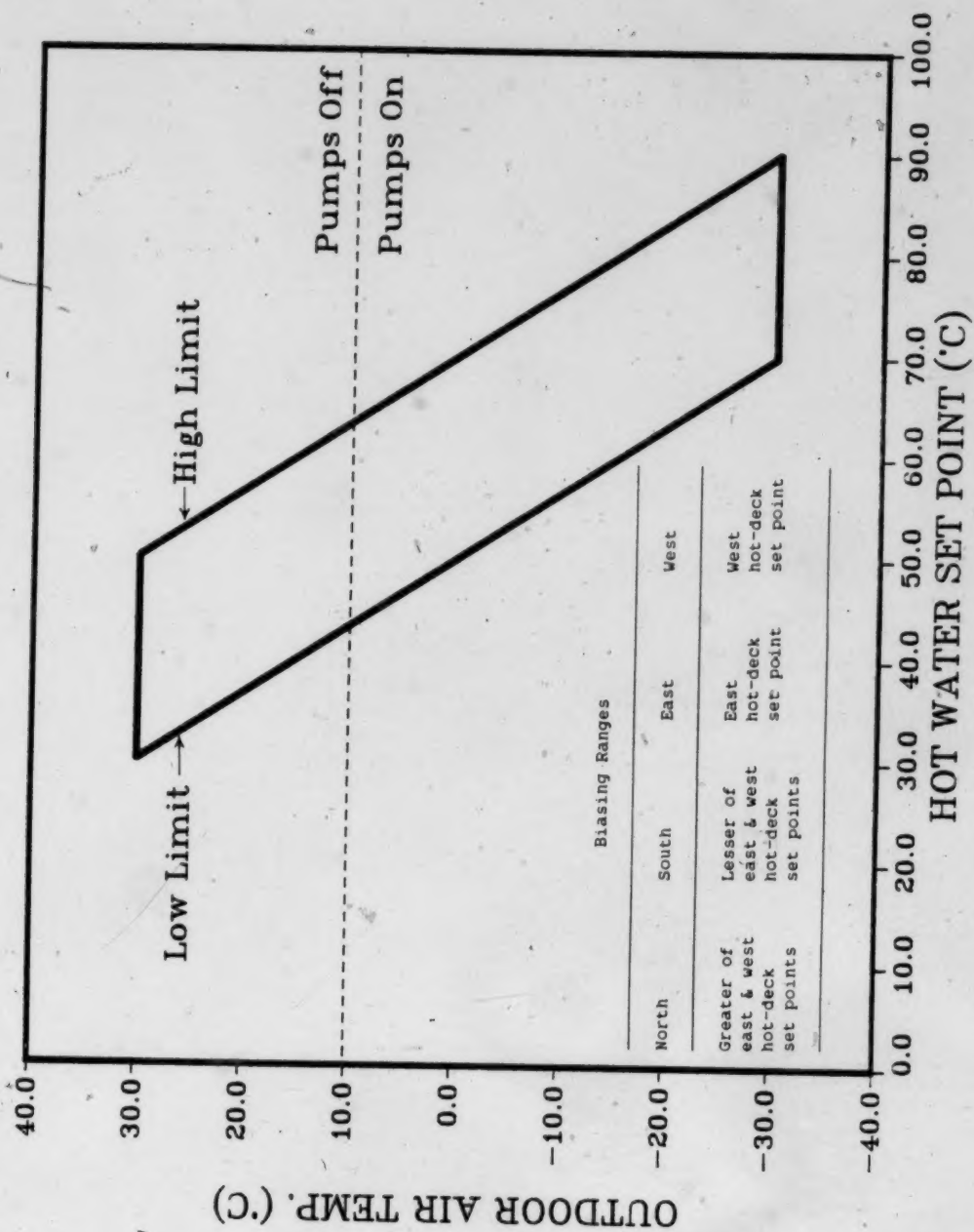


Figure 4.8 Existing radiation control.

Low pressure steam is used for domestic hot water, radiation heating, humidity control, and temperature control of hot ducts. Chilled water flows through cooling coils in the air-conditioning units. Fans, pumps, lights, office and kitchen equipment, elevators, et cetera, are all powered by electricity. All primary energy is supplied to the building from a central plant, via an underground tunnel. Energy flow to, within, and out of the pilot building is shown in Figure 4.9.

An energy audit was performed to determine the energy use patterns existing in the Administration Building. Historical measurements of gross steam and electrical power consumption were available. These were analyzed, whereupon estimates of subsystem consumption were made. No historical data of chilled water consumption was available.

Monthly measurements of gross steam consumption, from April, 1979 to March, 1984, are shown in Figure 4.10. The number of pumping cycles from the condensate tank were recorded and converted into pounds of steam. The pumping volume per cycle was calibrated each month. Variations in readings suggest monthly values are accurate to five percent.

Steam consumption has been greatest during the winter months, with monthly levels decreasing each fiscal year, except from 1980 to 1981. Variations between years have been significant, even when consumption levels are normalized with heating degree days. For example,

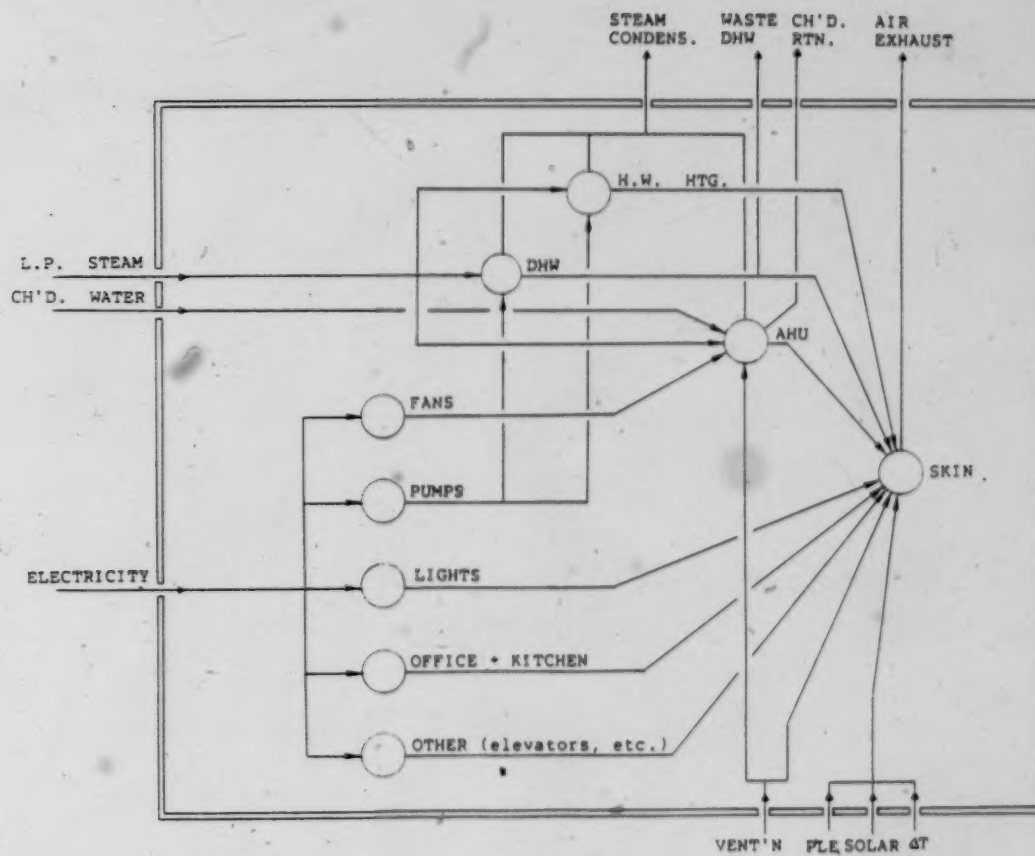


Figure 4.9 Energy flow sheet for the pilot building.

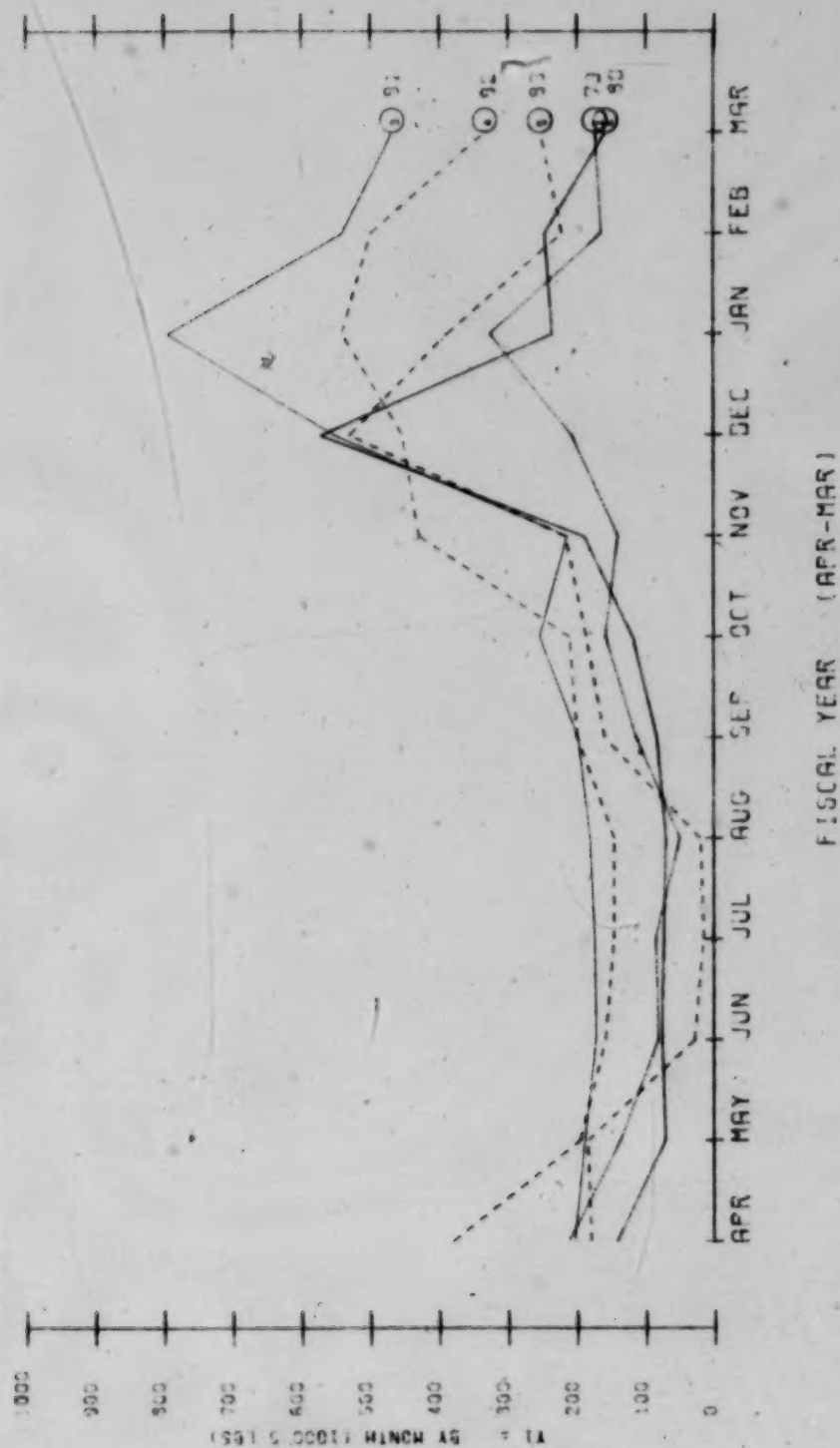


Figure 4.10 Fiscal year's steam consumption.

cumulative consumption increased by 93% from fiscal years 1980 to 1981, and decreased by 7% the following year. It can be assumed that weather patterns, usage patterns, operating strategies, metering errors, and/or occupancy levels over the last several years have been the major contributors to this erratic energy use.

Figure 4.11 shows the monthly electrical power consumption from April, 1979 to March, 1984. Electrical usage has been relatively constant from month to month, although there has been a consistent decrease over each fiscal year, since 1981. The general trend of decreased consumption is linked to conservation measures in lighting.

To quantify the success/failure of the proposed dynamic control system, the above information must be supplemented with a breakdown of energy flows within the building. This was possible for energy emanating from electrical and steam sources. Estimates of energy use were made from construction drawings and on-site measurements and observations. Details of these audits are given in Appendix A-2 and summarized in Tables 4.2a and 4.2b.

Chilled water supply to the Administration Building was not metered until *after* the start of dynamic control operation. Given that no historical records were available, weekly readings were recorded during dynamic control operation. Then, for a short period, operation without dynamic control was employed. This procedure, discussed in more detail in Section 4.3, proved to cause some

Table 4.2a Summary of electrical power audit.

Power Load Description	Percent of Annual Gross Power Load	Monthly Power Load (kW-h) 10
Computing & misc.	74.	111.
Service fans	11.	16.
Lighting	10.	15.
Service pumps	2.	3.
Elevators	2.	3.
Kitchen	1.	1.
Total	100.	149.

Table 4.2b Summary of steam heating audit.

Heating Load Description	School Period (Sept. to Apr.)		Summer Period (May to Aug.)	
	Monthly Heating Consump. (kW-h) 10	Percent of Total	Monthly Heating Consump. (kW-h) 10	Percent of Total
Dom. hot wat.	3.	3.	3.	7.
Space htg. & hum. contr.	92.	97.	35.	93.
Totals	95.	100.	38.	100.

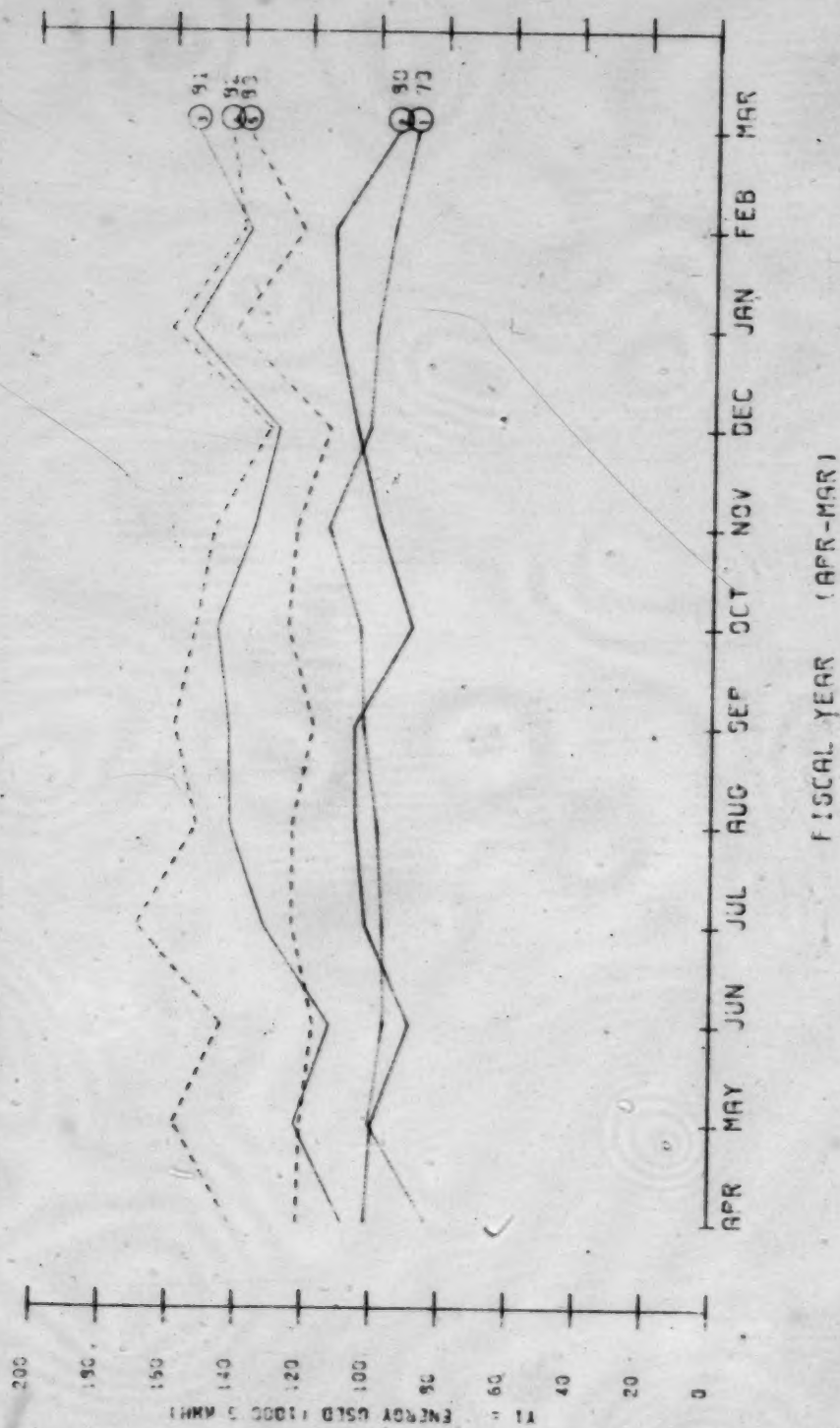


Figure 4.11 Fiscal year's electrical power consumption.

difficulties in determining the effect of dynamic control on energy consumption.

4.2 Retrofit Details

After the existing state of the pilot building was documented, a number of changes were made to initiate an environmental system which could operate under dynamic control. Local constraints such as monetary budgeting, time, and resource availability resulted in a control strategy differing in some aspects from the algorithms presented in Chapter 3. These differences are outlined below, followed by detailed sections on the mechanical, strategy and software changes made during the on-line development of the project.

Free cooling has been defined as the disabling of thermal inputs within an environmental control system. This operational mode was employed in the Administration Building, though its precise use differed from the theory in Chapter 3 as follows:

1. Instead of calculating the effective balance temperature range for which free cooling could be applied, free cooling was permitted whenever the outdoor temperature was between 0°C and 18°C, and when space temperatures were within specified ranges.
2. Whereas free cooling was defined (in Chapter 2) as operation without the addition of *any* thermal

inputs, the pilot control strategy permitted independent operation of the radiation system. For example, the AHU could be in free-cooling mode while the radiation pumps were on. This was found necessary due to the absence of local radiation control.

The application of thermal manipulation to the pilot building differed from the outlined theory as follows:

1. Chapter 3 identified two time periods when thermal manipulation can occur, namely, before occupancy and during the daytime. However, no daytime thermal manipulation program was integrated with the project's operation, since initial testing indicated that space temperatures could only be maintained within comfort bounds when a fixed temperature set point (of 22.7°C) was used during free cooling.
2. For preoccupancy operation, the algorithm proposed in Chapter 3 determined the optimum precooling duration by:
 - a. calculating the magnitude of the cooling load in excess of free-cooling capacity, and
 - b. calculating the rates of thermal charging and discharging.

The pilot algorithm instead determined the optimum duration through:

- a. forecasting the next day's maximum outdoor temperature,

- b. finding the desired mass temperature at the start of occupancy through a schedule of maximum outdoor temperature ranges, and
- c. calculating the duration of precooling required to achieve the desired mass temperature (based on the existing mass temperature and an adaptive algorithm).

This procedure greatly simplified these algorithms.

3. Because the cooling load in excess of the daytime free-cooling capacity was not calculated, there was no need to predict thermal load components, such as exterior conduction, ventilation, internal heat gains, et cetera.

Interior temperature drifting, the third component of dynamic control, was altered from the theory as follows:

1. Instead of having a variable-time warmup cycle using maximum system capacity, the pilot strategy initiated normal operating mode at 7:30 (a half hour before occupancy). A predictive software point adjusted the hot-duct set points according to existing space temperatures and forecasted outdoor temperatures. This procedure was used to keep the number of operating modes to a minimum, for the sake of simplicity.
2. An optimum stop program was not installed due to time constraints. Instead, the shut-down time was fixed at 17:00.

Between the months of February and May, 1984, the aforementioned algorithms for controlling the Administration Building were developed off-line. On-line development took place between May 15 and July 18 (1984), whereafter the control system was unaltered in any significant manner up to the end of evaluative monitoring (October, 1984). The following sections document the specific changes made during on-line development.

4.2.1 Mechanical Changes

Because the Administration Building was already linked to the campus RCMS, few mechanical changes were necessary. The areas which were physically altered included:

1. installation of new sensors, and
2. air balancing.

As part of the load prediction model development, a Li-Cor pyranometer sensor was installed on the roof of the pilot building, and connected to the PCM by cable. This Li-Cor (model LI-200SB) sensor, consisting of a silicon photovoltaic detector, was positioned to measure total horizontal solar radiation. Specifications for the sensor are listed in Table 4.3.

As noted in Section 3.2.1, thermal energy storage within an enclosure can be estimated by measuring the storage medium's temperature. On-line estimation of thermal storage is helpful during preoccupancy and daytime computations. In the case of the Administration Building,

Table 4.3 Pyranometer sensor specifications.

Item	Specification
Calibration	Calibrated against an Eppley Precision Pyranometer (PSP) under natural daylight conditions. Absolute error under these conditions is $\pm 5\%$ maximum, typically $\pm 3\%$.
Sensitivity	Typically $80 \mu\text{A}$ per 1000 Wm^{-2} .
Millivolt Output	10.0 mV per 1000 Wm^{-2} .
Linearity	Maximum deviation of 1% up to 300 Wm^{-2} .
Stability	Less than $\pm 2\%$ change over a one year period.
Response Time	$10 \mu\text{s}$
Temperature Dependence	Maximum of 0.15% per $^{\circ}\text{C}$
Size	23.8 mm diameter x 25.4 mm height.
Weight	$28. \text{ g}$

the majority of heat capacitance is contained within the concrete structure. It was therefore decided to embed one thermocouple in concrete at a location representative of the mean mass temperature. A 75 mm deep hole was drilled through an interior column, 1.4 m above the second floor slab. A thermocouple was then installed, covered with thermal-resistant glue, and linked to the PCM.

To ensure comfort constraints were realized, it was necessary to monitor maximum and minimum space temperatures. A survey of occupant comfort during the first days of free-cooling operation indicated that the basement rooms may experience the lowest space temperatures within the Administration Building. Since existing monitoring did not cover this area, two thermocouples were installed in Rooms 16 and 19²³.

While dynamic control operation was being developed, supply air flow rates through diffusers were measured and compared with design values. Most basement rooms and select areas on first and second floors were found to have higher flow rates than design values, whereas the third floor and certain second floor areas required more air volume. It was therefore decided to re-balance these areas. Although this work was not part of the dynamic control installation, it likely improved comfort conditions during free cooling.

²³ See Figure A-1.1 for location of basement rooms.

4.2.2 Operating Strategy

The operating strategy used for the pilot study was developed from the principles and algorithms discussed in Chapter 3, excepting a few minor changes. During a 24 hour period, beginning at 17:30, the following sequence of events take place under the new control system:

1. Off.
2. Precooling (when necessary).
3. Warmup.
4. Daytime operation (either normal or free-cooling modes).
5. Off.

To optimize these events, a number of operational modes were developed for the air-handling unit (AHU) and the radiation system. The four modes of operation used for the main AHU were:

1. off,
2. normal,
3. precooling, and
4. free cooling.

Off mode referred to associated fans and pumps in off position, with valves closed. Normal mode was similar to the existing control described in Section 4.1.2. That is, the AHU acted as a double duct system, with fixed cold-duct supply temperatures, and variable hot-duct supply temperatures. However, instead of the hot-duct controller set points being scheduled from the differential pressures

across the cold and hot ducts, they were scheduled from an empirical predictive temperature, calculated by the host computer. This enabled the normal mode to operate dynamically, and to act in a warmup mode before occupancy.

Precooling mode, operated before warmup, attempted to store cooling energy by lowering the temperature of the building's internal mass. During this mode, steam coils for the hot ducts were disabled, and cold-duct controller set points were set at 13°C. When the outdoor temperature dropped below 13°C, the chilled water coils were disabled.

Free cooling mode, which attempted to satisfy cooling loads for all zones without the addition of primary energy, disabled all heating and cooling coils within the air-handling unit. The mean resultant temperature for the building (that is, the average of the building mass temperature and average space temperature) reset the set point of the cold-duct temperature controllers. These controllers adjusted the mixed air dampers only.

A switching concept for each mode was used, with specific conditions for turning each switch on and off. Table 4.4 lists the switching combinations used to achieve the aforementioned modes.

System switch SY01 was programmed to turn on during weekdays either when the host called for precooling or at 7:30; it was programmed to turn off at 17:00, and remained off during weekends and holidays. The precooling switch, PC01, was turned on when the host requested precooling, and

Table 4.4 Air-handling unit switching combinations.

Mode	Times Permitted	Switching Status		
		System SY01	Precooling PC01	Free cooling EC01
Off	17:00-7:30	0	0	0
Normal	7:30-17:00	1	0	0
Precooling	17:00-7:30	1	1	0
Free cooling	8:00-17:00	1	0	1

Table 4.5 Conditions for free-cooling switch status.

Turn EC01 On If All Conditionals Met	Turn EC01 Off If Any Conditional Met
0 C < OAT < 18 C	0 C > OAT > 18
Ave. SPC.T > 21.4 C	Ave. SPC.T < 21.0 C
Ave. SPC.T < 23.2 C	Ave. SPC.T > 23.8 C
Max. SPC.T < 23.8 C	Max. SPC.T > 24.6 C
Min. SPC.T > 21.2 C	Min. SPC.T < 20.8 C
PC01 switch is off	PC01 switch is on
PC01 switch has been off for 30 minutes	SY01 switch turned off

Notes:

1. OAT = outdoor air temperature (dry-bulb).
2. SPC.T = space temperature.

always turned off at 7:30. Switch EC01 (free cooling) could be turned on any time between 8:00 and 17:00, as long as the conditions tested within the PCM were met. Once on, if any one of another set of conditions were met, it would be turned off. These EC01 on/off conditions are summarized in Table 4.5.

The radiation control system was altered to operate under two modes: one for daytime operation, including warmup, and one for nighttime operation, including precooling. Instead of being scheduled from select hot/cold duct differential pressures, hot water supply temperature biasing was controlled by demand, as determined by the average zone space temperature. The set point of the feedback controller was set to 22°C when normal or free-cooling AHU modes were invoked, and to 17°C during all other times. This demand biasing operated within a 10°C bracket above the (low-limit) outdoor temperature schedule. Pumps for the four zones were turned off whenever the hot water set point was below 50°C. (This would turn pumps off whenever the outdoor air temperature was above 12°C and there was a maximum demand from space temperatures. If there was no demand from space temperatures, pumps would be on continuously when air temperatures were below 0°C.)

The aforementioned operating schedules and switch statuses were controlled at PCM and/or host levels. Since communication could be lost between the host and PCM, control functions were placed so that satisfactory operation

could be realized without host support. For example, switch PC01 was normally turned off by the host at 7:30. However, if the host were to fail, a backup time clock in the PCM would turn off PC01 at 7:45. Location of software control is summarized in Table 4.6.

4.2.3 Software Changes

Software for the Administration Building which existed prior to the pilot project attempted to achieve steady-state conditions through real-time feedback operation. This software was modified at the host and PCM levels during the pilot development stage. Sophisticated algorithms were placed at the host level for both preoccupancy and daytime operation. These included:

1. a precooling algorithm, to be run during non-occupancy periods, and
2. a daytime algorithm, used in normal operating mode and during warmup.

Both of these programs were supported by a load prediction model. These algorithms will be discussed in the order they were developed; that is:

1. the load prediction algorithm;
2. the precooling algorithm; and
3. the daytime algorithm.

Load prediction. During the off-line development period, two load prediction models were developed. Initially, a general model was considered which could be

Table 4.6 Location of software control.

Point	Turned on by	Turned off by
SY01	Host	Host
PC01	Host	Host / PCM time backup
EC01	PCM	PCM
S007	Host	--

used in any large building. Later, a less sophisticated model (applicable to the Administration Building only) was developed and used in the other two control algorithms. An adaptive approach was not possible for either model due to the absence of historical data and the lack of time available to use detailed simulation techniques.

An outline of the computing process developed for the initial prediction model is illustrated in Figure 4.12. Inputs included real time (including day of the year), outdoor dry-bulb temperature, and total horizontal solar radiation. These two weather inputs were forecasted, followed by predictions of fenestration and conduction heat fluxes. Finally, the predicted total load was taken as the sum of the following calculated loads:

1. External load.
2. Ventilation load.
3. Internal load.

The weather parameters selected for the initial model were chosen because of their potential significance in

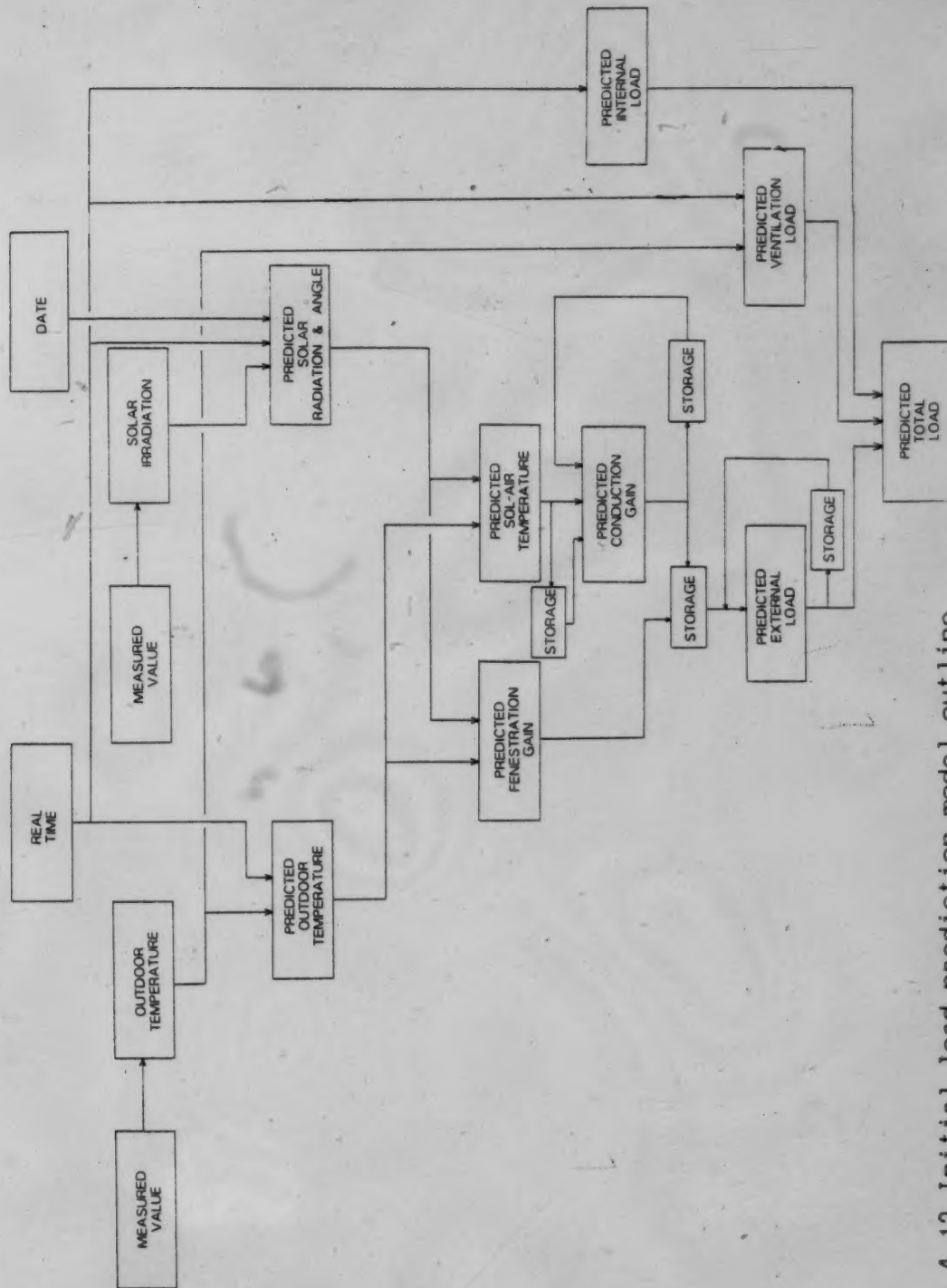


Figure 4.12 Initial load prediction model outline.

certain buildings. Speed and direction of the wind were not included, since ASHRAE (1981) notes that, in large buildings, the gross ventilation load depends more on the controlled ventilation system than on the performance of the building envelope.

An outdoor temperature forecasting model was developed, based on the technique outlined by Hittle (1981). Fourier coefficients (a_0 , a_1 , b_1 , a_{365} , etc.) were determined by Fast Fourier analysis, using hourly weather records from the Edmonton Municipal Airport weather station. Daily and half-daily coefficients were calculated using 720 hourly values, sampled at different times of the year, for years 1953 and 1954. Daily averages (of hourly data) over a ten year period (1953 to 1962) were used to calculate a_1 and b_1 . Equation (3-18) was then modified to take into account the availability of real-time measurements. The final model used the following equations:

$$T_{n+i} = T_b + 2\{1.80\cos[0.2618(n+i)] + 1.23\sin[0.2618(n+i)]\} - 2\{0.05\cos[0.5236(n+i)] - 0.13\sin[0.5236(n+i)]\} \quad (4-1)$$

where:

- n - real-time hourly counter ($0 \leq n \leq 23$),
- i - number of hours beyond real time,
- T_{n+i} - forecasted outdoor temperature at time, $n+i$, and
- T_b - base temperature, calculated from measured (real-time) temperature;

$$T_b = T_n + 2[1.80\cos(0.2618n) + 1.23\sin(0.2618n)] - 2[0.05\cos(0.5236n) - 0.13\sin(0.5236n)] \quad (4-2)$$

In forecasting the effect of solar radiation, two algorithms were developed--one for forecasting during dark hours, and one for forecasting during daylight hours using real-time measurements. For dark-time forecasting, a sinusoidal model in the form of Equation (3-17) was developed for predicting total horizontal radiation (I_{th}) and diffuse radiation (I_{ds}). Values for Fourier coefficients were calculated from hourly medium values for each month. These values were taken from Environment Canada's Atmospheric Environment Service Stoney Plain²⁴ station records.

For daytime forecasts, real-time measurements of I_{th} were compared to calculated clear-sky total horizontal radiation for the same time. In this manner, an estimate of I_{ds} could be made, using the following formula proposed by Duffie and Beckman (1974):

$$\begin{aligned} I_{ds}/I_{th} &= 1.00 - 0.1a & 0 \leq a < 0.48 \\ &1.11 - 0.0396a - 0.789a^2 & 0.48 \leq a < 1.10 \\ &0.20 & 1.10 \leq a \end{aligned} \quad (4-3)$$

where $a = I_{th}/I_c$ and I_c is the total clear-sky horizontal radiation.

²⁴ Stoney Plain is located approximately 50 km west of Edmonton.

With solar radiation and outdoor temperature forecasted, the initial model then calculated the resulting heat fluxes and cooling loads, based on the Transfer Function Method outlined in ASHRAE (1981).

Infiltration load was calculated assuming the only driving force was thermal buoyancy (stack effect) caused by a temperature difference between indoor and outdoor air. Once the theoretical pressure (P) induced from stack effect was calculated, the infiltration load was estimated by:

$$L \cong EAPEC_i D_i \cdot \exp(N_i) \quad (4-4)$$

where:

- L - volumetric flow rate into building (excluding mechanical ventilation),
- E - entrance-way traffic factor, a function of time,
- C_i - flow coefficient,
- D_i - length of crack, or area of surface,
- N_i - flow exponent, corresponding to C_i, and
- exp - exponential e.

Thermal conduction through the exterior envelope was calculated using an effective sol-air temperature for each surface type. Transfer function coefficients for the wall and roof construction specific to the Administration Building were taken from ASHRAE (1981).

The last prediction in the generalized model was the internal cooling load. Since occupancy patterns are relatively constant from one day to the next in the pilot

building (excepting weekends and holidays), it was possible to calculate the internal hourly load off-line. The hourly electric profile was monitored, and a lighting and occupant count was performed to help estimate the resulting loads. The Cooling Load Factor (CCF) Method outlined in ASHRAE (1981) was then used for load calculations. Figure 4.13 summarizes the calculated internal load profile.

A listing of the initial program developed for load prediction is provided in Appendix A-3.

The aforementioned load prediction model was developed to gain insight into all possible routines which could be required in a non-adaptive load prediction model. However, as Section 5.2.1 will detail, the Administration Building's high internal load is the dominating factor in cooling load calculations (during the cooling season). It was therefore decided to employ a greatly simplified load prediction model to support the real-time daytime control algorithm. This prediction model was based on the following empirical formula developed by the author:

$$Q_{n,t} \cong Q_{i,t} + \lambda I_{th} \quad (4-5)$$

where:

$Q_{i,t}$ - internal cooling load, at time t , and

λ - solar importance factor ($\lambda \geq 0$).

Precooling algorithm. The preoccupancy algorithm developed for the pilot project was based on the four factors outlined in Section 3.2.1; namely:

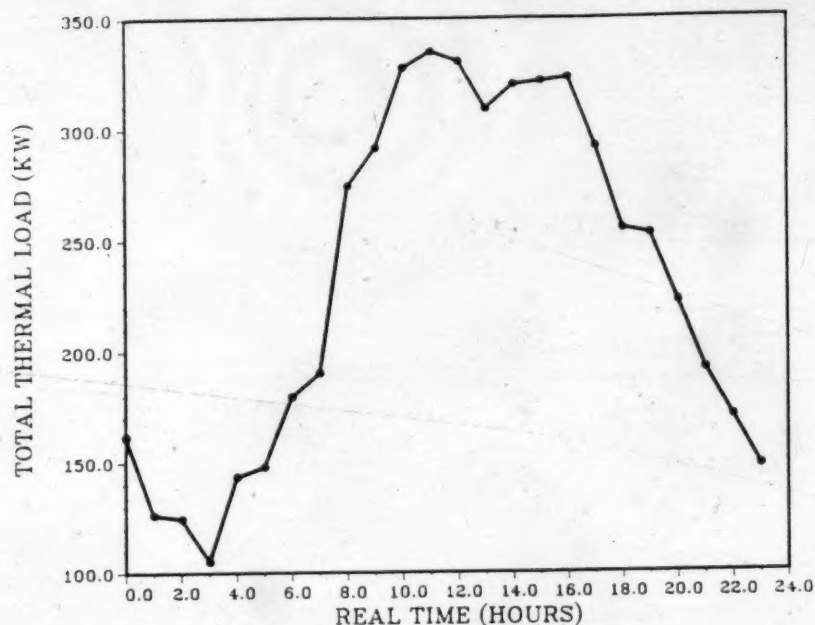


Figure 4.13 Estimated internal cooling load for the Administration Building.

1. excess load,
2. rate of depletion,
3. rate of charging, and
4. optimum charging.

Preliminary analysis of forecasts indicated that computations could be easily simplified by replacing the excess load (Edf) with the forecasted maximum temperature. The relationship between these two variables was found (by simulation studies) to be approximately linear²³, as shown in Figure 4.14.

Another way in which computations were simplified was the development of a charging schedule based on the average mass temperature, T_m , and the forecasted maximum outdoor

²³ This observation is specific to the pilot building.

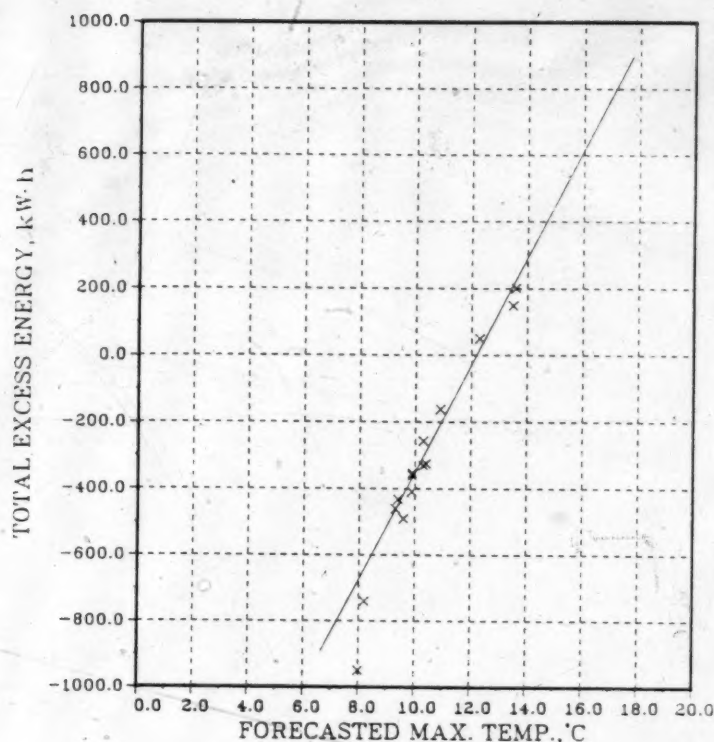


Figure 4.14 Relationship between Edf and Forecasted maximum outdoor temperature.

temperature, T_{mx} . Instead of being developed through off-line simulation studies, this schedule was first estimated. Then, when the dynamic control system was being tested on-line, the schedule was altered according to the observed thermal response of the building. Table 4.7 lists the final schedule that was developed.

The precooling algorithm was programmed to run once an hour at 30 minutes after the hour, from 17:30 to 7:30. During each run, the computer would read real-time data, determine T_{mx} , and find the desired mass temperature for 7:30 (T_m) from Table 4.7. Next, the duration of precooling would be calculated using the formula:

Table 4.7 Pilot precooling schedule.

Forecasted Maximum Outdoor Temperature (°C)	Targetted Mass Temperature at 7:30 (°C)
$T_{omx} \leq 10.$	*
$10. < T_{omx} \leq 16.$	23.5
$16. < T_{omx} \leq 24.$	23.1
$24. < T_{omx}$	22.7

* No precooling permitted.

$$\Delta t = (T_m - T_{m_7}) / K_m \quad (4-6)$$

where:

Δt - precooling duration (before 7:30),

T_{m_7} - present value of T_m , and

K_m - mass temperature rate.

The mass temperature rate was a predictive-adaptive parameter, corrected at 7:30, using the autoregressive formula:

$$K_{m_n} = 0.125K_{m_{n-4}} + 0.130K_{m_{n-3}} + 0.135K_{m_{n-2}} + 0.160K_{m_{n-1}} \quad (4-7)$$

where n equals the current day. As noted by Shavit (1980), the weighting factors in Equation (4-7) can be determined either experimentally or through simulation programs. As neither of these methods were available (due to time and budgeting constraints), these factors were estimated (as

indicated) through observation at the initial stages of implementation.

The calculated value of Δt was restricted to a range dependent on $T_{o_{mx}}$ and $T_{m,}$, as detailed in Table 4.8. This was imposed to ensure calculated values of Δt were "reasonable" for these two parameters.

Figure 4.15 presents a summary flow chart for the precooling algorithm employed.

Daytime algorithm. The daytime algorithm, scheduled to run once an hour, permitted normal operating mode to handle both the warmup cycle and normal operation (excluding free cooling). This was achieved by scheduling the hot-duct controller set points from a calculated empirical temperature, T^* .

T^* represents the predicted cooling requirement for the Administration Building. Its value was calculated from an empirical equation, which was based on the time series solution for predicting room temperatures. This solution, represented by Equation (3-14), was simplified by considering only one time interval, so that:

$$Ta'_i \cong a - \beta_1 Ta'_{i-1} + \gamma_0 Qd_i \quad (4-8)$$

Next, T^* was introduced into Eq. (4-8) by letting T^* equal $(Ta'_i - a)$, so that:

$$T^* = -\beta_1 Ta'_{i-1} + \gamma_0 Qd_i \quad (4-9)$$

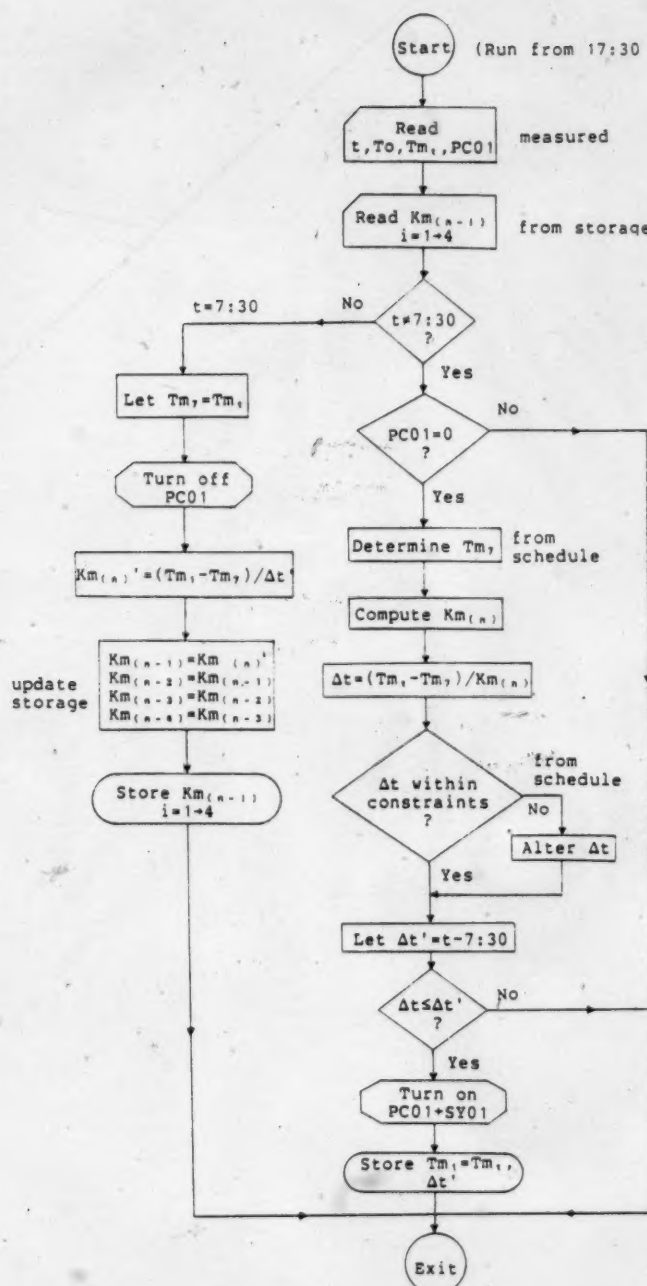


Figure 4.15 Flow chart illustrating the precooling algorithm.

Table 4.8 Precooling constraint schedule.

Forecasted Max. Temp. ($T_{o_{mx}}$) (°C)	Current Mass Temp. (T_{m_i}) (°C)	Limits of Precooling Duration (Δt) (h)
$T_{o_{mx}} \leq 10.$	Any	0.
$10. < T_{o_{mx}} \leq 16.$	$T_{m_i} \leq 23.5$ $T_{m_i} > 23.5$	$1. \leq \Delta t \leq 3.$ $1. \leq \Delta t \leq 5.$
$16. \leq T_{o_{mx}} < 24.$	$T_{m_i} \leq 23.5$ $T_{m_i} > 23.5$	$2. \leq \Delta t \leq 6.$ $2. \leq \Delta t \leq 8.$
$T_{o_{mx}} \geq 24.$	$T_{m_i} \leq 23.5$ $T_{m_i} > 23.5$	$3. \leq \Delta t \leq 10.$ $3. \leq \Delta t \leq 12.$

As only a few weeks of monitored data were available during the development of the daytime algorithm, values for β , and γ could not be determined accurately. Instead, their respective values were estimated (through trial and error) to be -1.00 and 0.005 respectively.

During normal operation, maximum hot-duct temperatures were scheduled when T^* was 21°C or less, and minimum when T^* was equal to or greater than 25°C .

During the first two hours of daytime occupancy, the calculated value of T^* was altered to permit normal operating mode to act as a warmup mode. Following the concepts outlined in Section 3.3.2, it was argued that space temperatures during the initial period of occupancy should be permitted to be below (or above) the desired set point, in proportion to:

1. the forecasted maximum outdoor temperature, and
2. the time of day.

Table 4.9 details the action taken to alter the value of T^* at 7:30 and 8:30.

Appendix A-4 presents a complete listing of the host computer program used for preoccupancy, warmup, and normal operation.

4.3 Testing Procedures

Evaluation of the pilot project was carried out between May 25 and November 19, 1984. During this period, general documentation, on-line monitoring, and an occupant survey were performed. These testing procedures helped to evaluate:

1. free cooling operation,
2. host real-time programs,
3. comfort, and
4. use of energy and other resources.

Any extraordinary events, such as system failures, were documented and summarized weekly. Concurrently, a number of state variables were measured hourly and recorded by the RCMS data acquisition system. Table 4.10 lists all the hourly, weekly, and monthly records maintained.

Free cooling operation and host programs were not evaluated on a comparative basis. Instead, select elements were statistically described. Comfort and energy use, however, were compared to base-line values (i.e., operation without dynamic control).

Table 4.9 Pilot building warmup schedule.

Time (h)	OAT Reading (°C)	Tbldg. (S006)	Action Taken
7:30	0. <OAT < 6.	<22.3 >22.3	IF(S007.LE.23.0) S007=23.0 S007=25.
	6. <OAT < 12.	<22.0 >22.0	IF(S007.LE.23.5) S007=23.5 S007=25.
	12. <OAT	<21.0 >21.0	IF(S007.LE.24.0) S007=24.0 S007=25.
8:30	OAT < 6.	<22.6 >22.6	IF(S007.LE>23.0) S007=23.0 S007=25.
	6. <OAT < 12.	<22.3 >22.3	IF(S007.LE.23.5) S007=23.5 S007=25.
	12. <OAT	<21.8 >21.8	IF(S007.LE.24.0) S007=24.0 S007=25.

As the ultimate measure of comfort is the subjective experience of occupants, a paper and pencil questionnaire was distributed between November 14 and 19, 1984. Occupants of the Administration Building were asked how their level of thermal comfort had changed from the summer of 1983 to the summer of 1984. A sample questionnaire is provided in Appendix A-5.

After data collection, various analyses were performed using FORTRAN with a main-frame computer. These results are presented and discussed in the following chapter.

Table 4.10 Data monitored during testing period.

Frequency	Period Of Monitoring (1984)	Records Available
Hourly	Feb 01 - Oct 25	Time Date Outdoor air temp.
	Feb 01 - Apr 19	Forecasted variables: -outdoor air temp. -solar radiation -fenestration load -conduction load -infiltration load -internal load -total thermal load
	Apr 19 - May 07	Excess load
	May 07 - Sep 26	Calc'd. precool. duration Self-adaptive constant for precool. algorithm Forecasted max. temp. Real-time mass temp. SY01 status EC01 status PC01 status
	Jul 09 - Sep 26	S007 status
	Sep 27 - Oct 25	SY01 status EC01 status PC01 status Max. space temp. Min. space temp. Ave. space temp. Mass temp.
Weekly	Jun 04 - Oct 25	Deg. hours (clg.)/week Est. ch'd. wat. (HVAC) consump. Est. stm. htg. (HVAC) consump. Est. elect. pwr. (HVAC) consump.
Monthly	Jun 01 - Sep 01	Tot. ch'd. wat. consump. Tot. stm. htg. consump.

5. RESULTS AND DISCUSSION

The results and discussion which follow focus on the main objective of this study. By identifying and analyzing significant outcomes of a specific application of dynamic control, it was hoped that the general guidelines developed in Chapters 2 and 3 could be evaluated and discussed. It should be noted that the emphasis of this chapter is not to evaluate the relative merit of dynamic control (compared to alternate control strategies), but rather to evaluate the strategy on an absolute basis.

Three general concepts of dynamic control (i.e., free cooling, thermal inertia, and interior temperature drifting) are evaluated in this chapter. Free cooling is discussed in terms of its potential application (theoretical versus actual). Next, the host algorithms developed for the pilot study are evaluated. Finally, this chapter quantifies the success of implementation through an evaluation of the thermal comfort and resources expended (particularly energy).

5.1 Free-Cooling Operation

Of all the concepts relating to dynamic control, free cooling is the most essential in reducing the amount of energy spent. For example, whenever the main AHU of the Administration Building was operating in normal or warmup modes, thermal energy was required to maintain a temperature differential between hot and cold ducts. However, when free

cooling switch EC01 was on, this thermal energy was not consumed (since heating and cooling coils were disabled).

By comparing the number of hours switch EC01 was on to the total number of daytime operating hours, an indication of free cooling potential and its associated energy savings can be made. From the data acquired over the 1984 monitoring period, the percentage of free cooling occurrences for each 1.0°C outdoor temperature band was calculated. The results are plotted in Figure 5.1. Periods surrounding system failures and readings from 17:00 to 8:00 were excluded.

When interpreting Figure 5.1, it should be realized that less than 50 readings were available for periods monitored below 10°C ²⁴. This affects the confidence of results within the bands below 10°C . Accepting this, there appears to be an outdoor temperature range for which free cooling can be expected to occur. This observation confirms the concept of an effective balance temperature range discussed in Section 3.1.1. Within this range (i.e., approximately 4°C to 22°C), free cooling will not occur all of the time due to variations in internal load, solar radiation, interior space temperatures, et cetera.

²⁴ This was a result of the temperature patterns which occurred during monitoring.

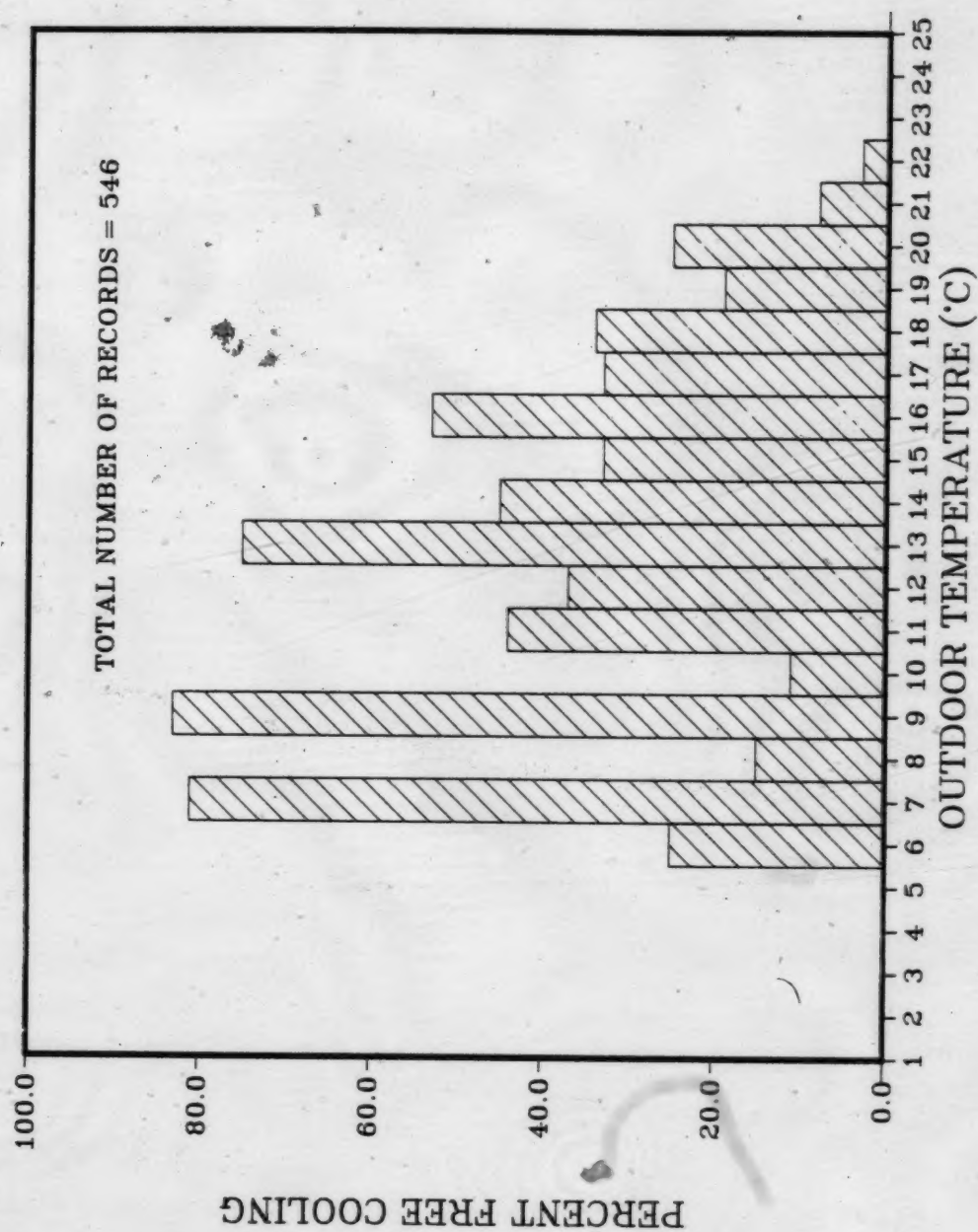


Figure 5.1 Percent of free cooling occurrences for different outdoor air temperatures.

5.2 Thermal Inertia Algorithms

To maximize the percentage of free cooling occurrences, a strategy was developed which would manipulate the thermal mass of the pilot building. Since this would be a dynamic process, a thermal prediction model first had to be developed. Afterwards, a control algorithm for precooling was created. Both of these developments are discussed below.

5.2.1 Thermal Load Prediction

Since historical data of thermal load Q_n and its associated inputs (e.g., outdoor temperature, time, etc.) were not available for the pilot building, the load prediction models developed could not employ an adaptive approach. Instead, each key parameter was forecasted, so that the total load could be taken as the algebraic sum of the contributions from each input.

The first load prediction model developed, as detailed in Figure 4.12 and Appendix A-3, considered outdoor air temperature, solar radiation, and time as inputs. As discussed in Section 4.2.3, separate prediction algorithms were developed for each input. The accuracy of these modules (i.e., algorithms) was found to be acceptable for the related control decisions for this building. For example, a typical 24-hour forecast of outdoor (dry-bulb) temperature is shown in Figure 5.2. Whereas outdoor temperature was assumed to be sinusoidal, this plot

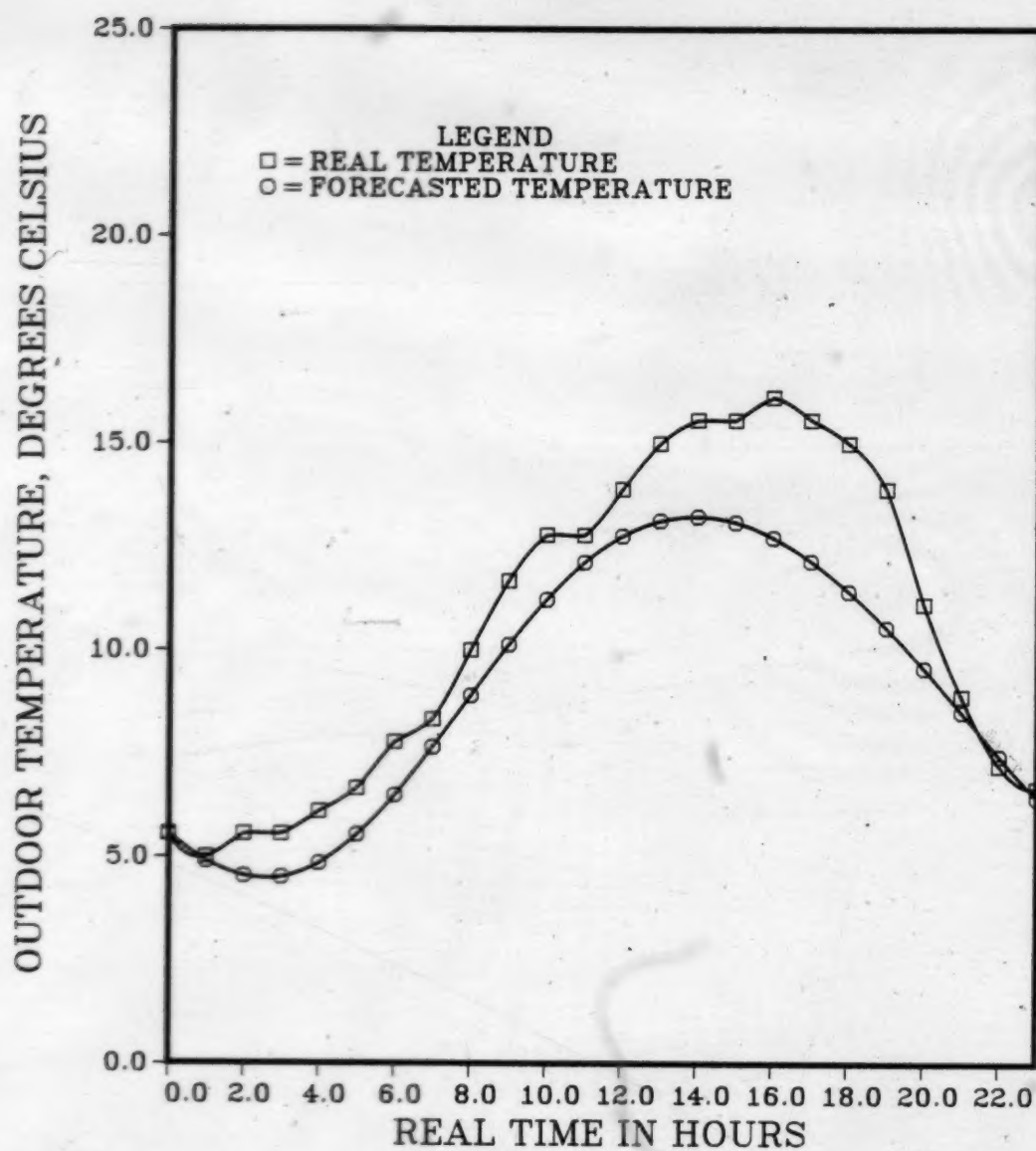


Figure 5.2 Actual versus forecasted outdoor temperatures for March 4, 1984.

demonstrates that it is also stochastic. Nevertheless, forecasted values do follow the real measurements to a large degree.

The error incurred by using this temperature model was analyzed using ten sets of 24 hour forecasts. The mean absolute error (between actual and forecasted values) was found to be a function of the number of hours beyond real time, as illustrated in Figure 5.3. For the first six hours, the error is nearly a linear function of time. However, beyond this, a cyclic pattern is observed, likely due to the lack of higher harmonics in the prediction model. A maximum error of under $\pm 5^{\circ}\text{C}$ can be expected for forecasts up to 24 hours beyond real time.

Since the final control algorithm employed only used forecasted maximum temperatures, a typical day of such forecasts is shown in Figure 5.4. For each hour, the real-time measurement for that hour was used to forecast next day's maximum temperature. The value at 18:00 (hour 1) is much higher than the other forecasts because calculations were based on readings from the northern outdoor thermocouple of the Administration Building, which was exposed to solar radiation at that time. The other readings were taken after sunset. Note that the forecasted maximum does not vary significantly from one hour to the next.

As another example of the prediction modules used in the initial load prediction model, Figure 5.5 shows a typical 24 hour forecast of total horizontal radiation.

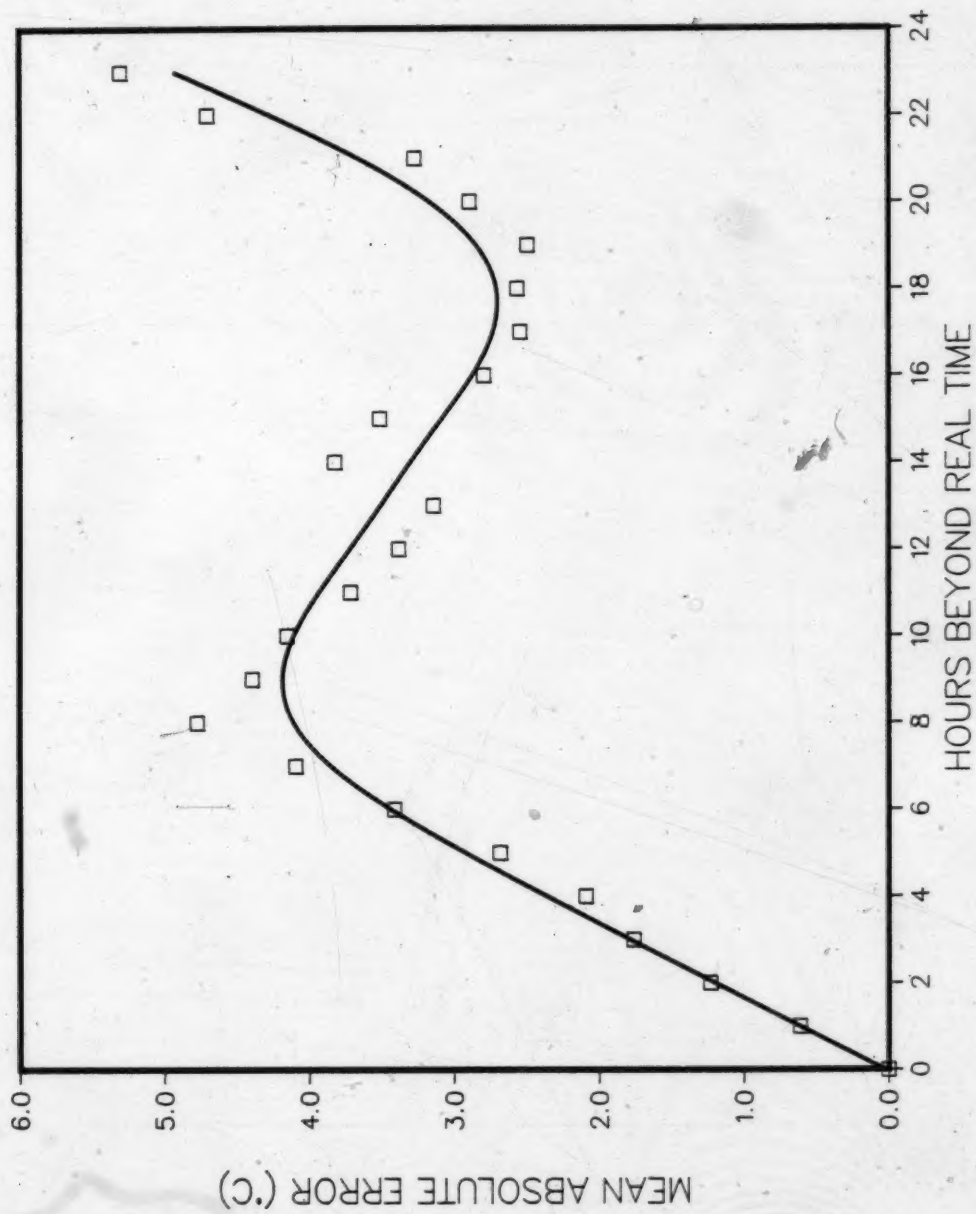


Figure 5.3 Forecasting error versus hours from real time for outdoor temperature predictions.

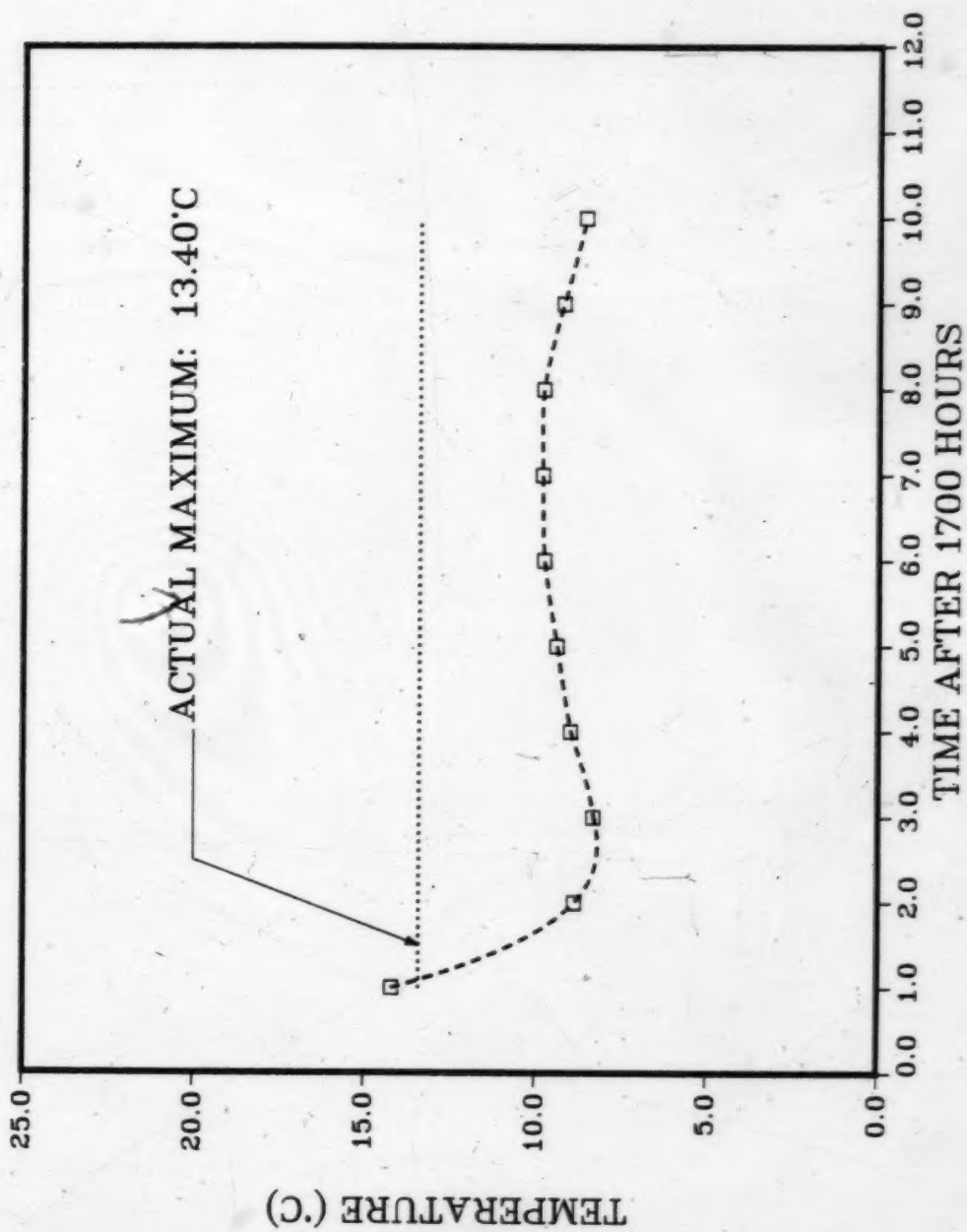


Figure 5.4 Maximum outdoor temperature forecasts made during May 24, 1984.

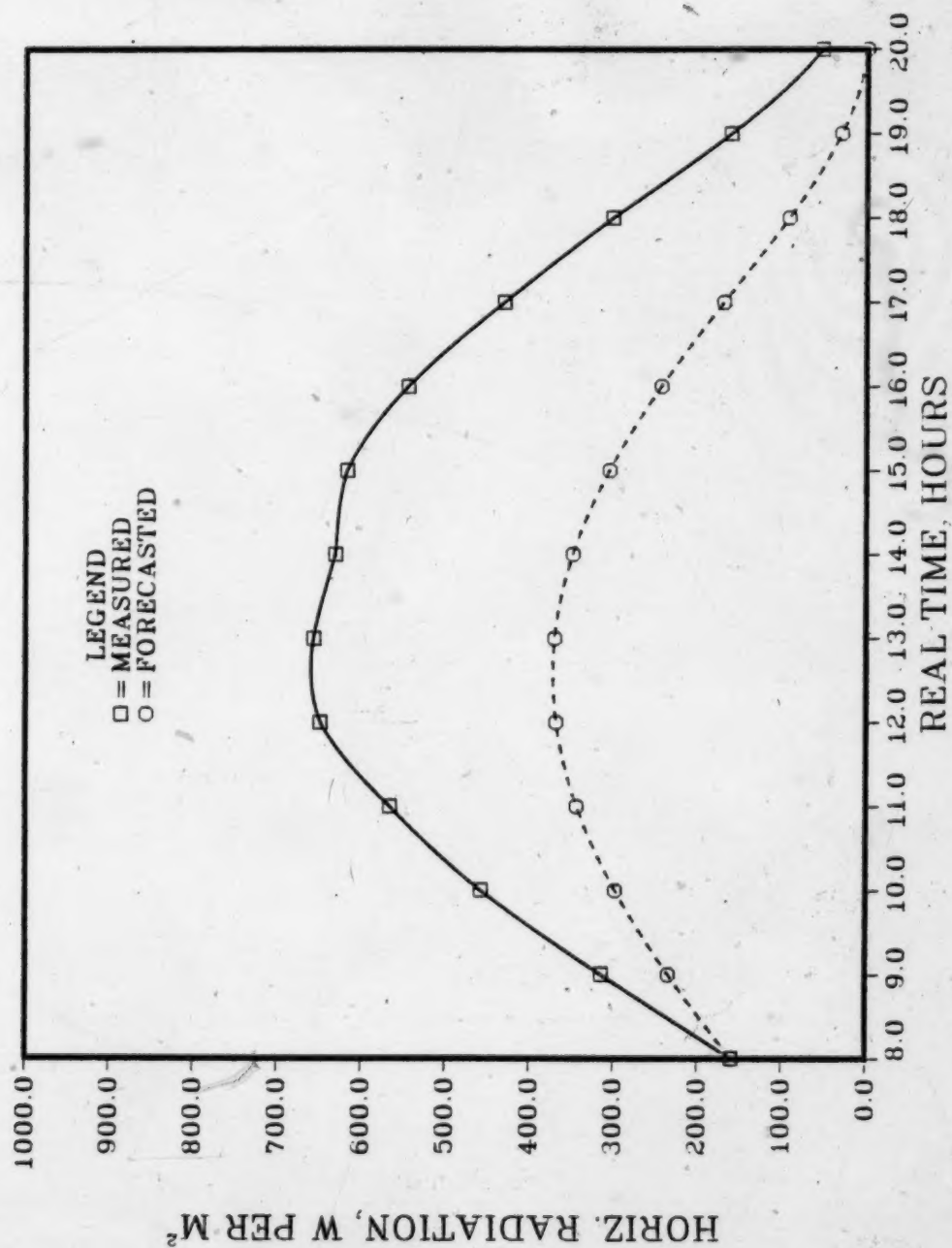


Figure 5.5 Actual versus forecasted total horizontal solar radiation for March 4, 1984.

Errors in forecasting solar parameters were found to be much larger than with the outdoor temperature forecasts. This is largely due to the variations in cloud cover. For example, the day for which Figure 5.5 was plotted experienced early morning cloud cover. Soon after 8:00, this cover vanished so that clear-sky conditions existed for the remainder of the day. Since the forecast shown was based on the real-time conditions existing at 8:00, the resulting forecast was in error by as much as -300 W/m^2 .

In evaluating these various forecasting modules, it is important to consider the level of contribution each input has on the total load (Q_n). This will depend on the building and its location. Analysis of the Administration Building indicated that the effects of solar radiation and outdoor temperature on total load were relatively small for the outdoor temperature range in which dynamic control could be expected to operate (i.e., 4°C to 22°C). For example, Figure 5.6 shows a typical load situation for spring conditions. Internal load (a function of time-of-day) makes up 90% of the total load; infiltration (a function of outdoor temperature) contributes approximately 4%; and conduction and fenestration (functions of outdoor temperature and solar radiation) together only form roughly 7% of the load.

This variation in contribution has significant implications on how a prediction model should be developed. For example, a 50% error in a solar radiation forecast for

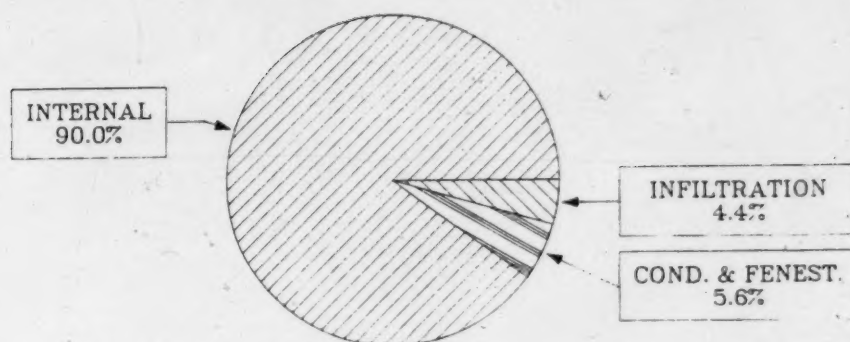


Figure 5.6 Composition of total thermal load for April 10, 1984 at 14:00.

the pilot study would only result in less than a 3% error in the total load prediction. It was from this observation that the final, greatly simplified, prediction model was developed.

As discussed in Section 4.2.3, the final model developed only considered internal load and an empirical function of the horizontal solar radiation reading. Despite this simplification, acceptable forecasts resulted. As an example, a 15-hour prediction, using the final load model, was made. Values were compared to those calculated using the initial load model, using real-time ("measured") data. As shown in Figure 5.7, the accuracy of this final model was acceptable.

The change from the initial to the final load program marked a great reduction in computing time. For example, the initial model had over 700 program lines and took approximately one minute to run on the host, whereas the final model had approximately 60 program lines, and took

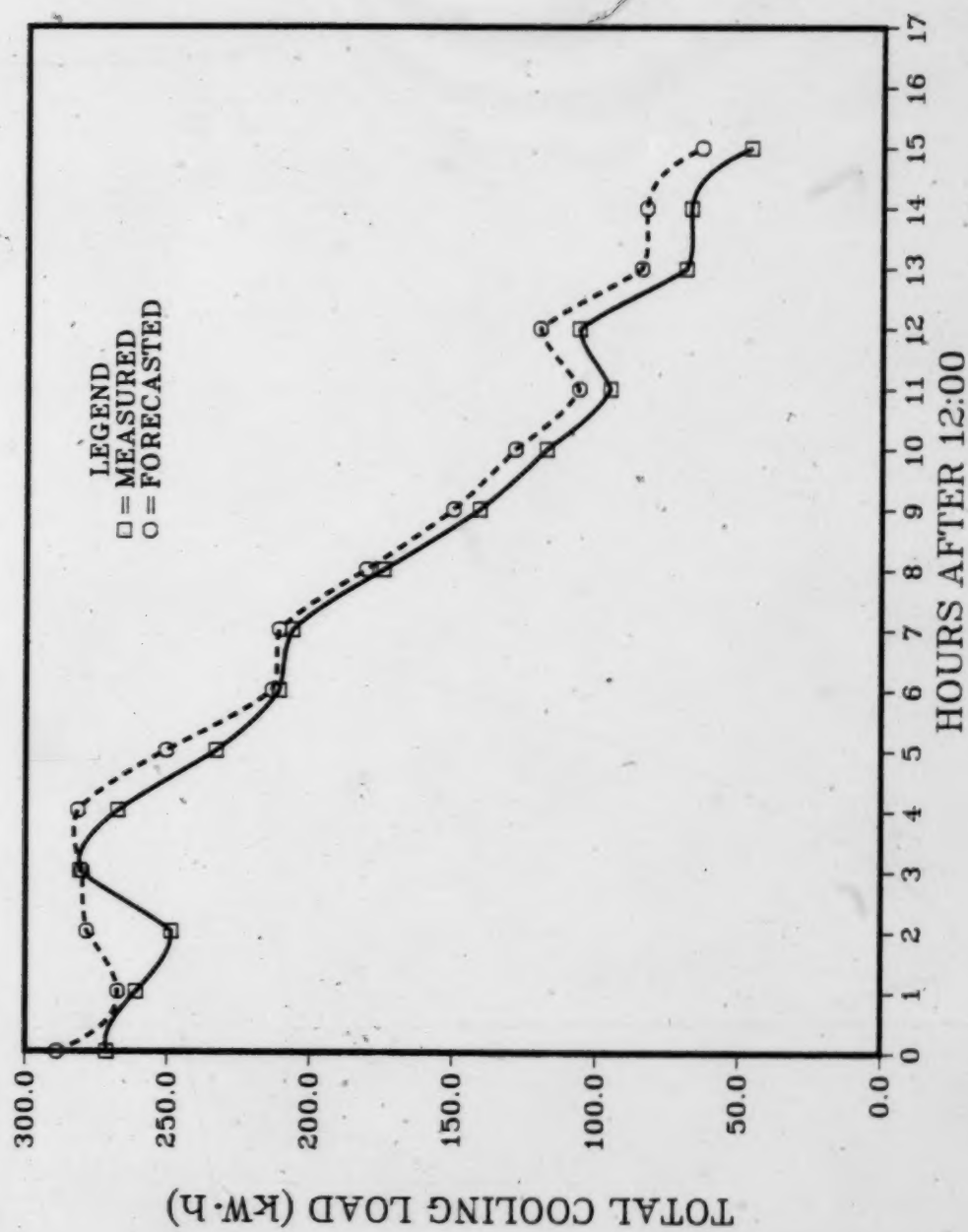


Figure 5.7 Forecasting total thermal load from 12:00 on April 10, 1984.

under five seconds to run.

5.2.2 Preoccupancy Algorithm

The preoccupancy algorithm, listed in Appendix A-4, determined the estimated optimum duration of precooling before 7:30. Inputs for this computation included:

1. forecasted maximum outdoor air temperature,
2. real-time average building mass temperature, and
3. self-adaptive constant vector {Km}.

The average mass temperature (T_m), measured from a thermocouple embedded in an interior column of the Administration Building, was found to be marginally affected by space temperature fluctuations experienced during the daytime. This is shown in Figure 5.8, where a 1°C rise in average space temperature over six hours (i.e., from 7:00 to 13:00) did not significantly alter the interior mass temperature²⁷. However, during precooling, the average mass temperature was able to be lowered, at an average rate of 0.25°C/h .

Before the average mass temperature rate Km could be determined (through data acquisition), an adaptive approach was used. The last four calculated values of Km were used in Equation (4-7) to estimate Km for the current period. The actual values of Km (calculated after each precooling

²⁷ The lack of correlation between the two variables in Figure 5.8 is partly a result of the mass temperature reading being at a specific location, whereas the space temperature is the average of several readings at different locations within the building.

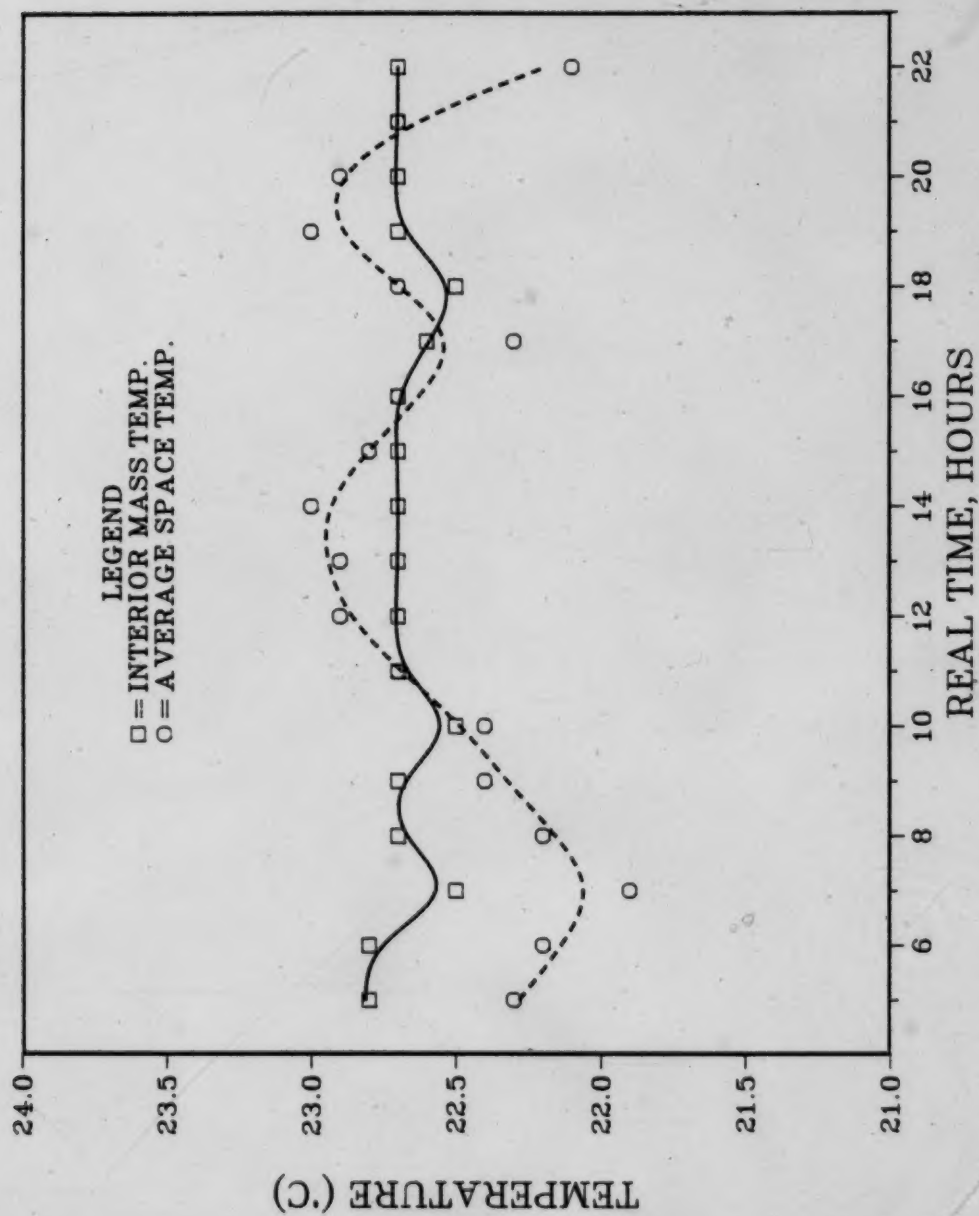


Figure 5.8 Variations in space and mass temperatures during October 1, 1984.

cycle) are compared to the predicted values (calculated before each cycle) in Figure 5.9.

After the first several days of operation, K_m was found to frequently vary up to 50% from its average value. Although it was hoped that the self-adaptive approach taken would be able to predict these variations, analysis performed at the end of monitoring revealed that the root mean square (RMS) error using the average value of K_m was less than the RMS using Eq. (4-7). However, this may have not been the case if Eq. (4-7) had used calculated coefficients²¹ instead of estimating them. Such calculations were not performed.

Although forecasted maximum temperature did influence the calculated duration of precooling, the existing mass temperature, representing the amount of energy stored within the structure, had a greater effect. This is demonstrated in Figure 5.10. Although there is a general trend of increased precooling duration for higher outdoor temperatures, there is a large scatter in the plot due to the variation in heat buildup for any given day. For example, a greater number of hours of precooling were required for Mondays and Tuesdays due to the heat built up over the weekends²².

²¹ These coefficients can be determined through time series analysis. See Box and Jenkins (1976).

²² Frequently during monitoring, the mass temperature would reach 24°C or higher by Sunday evening. Generally, it would take two days to lower the mass temperature by 0.5°C.

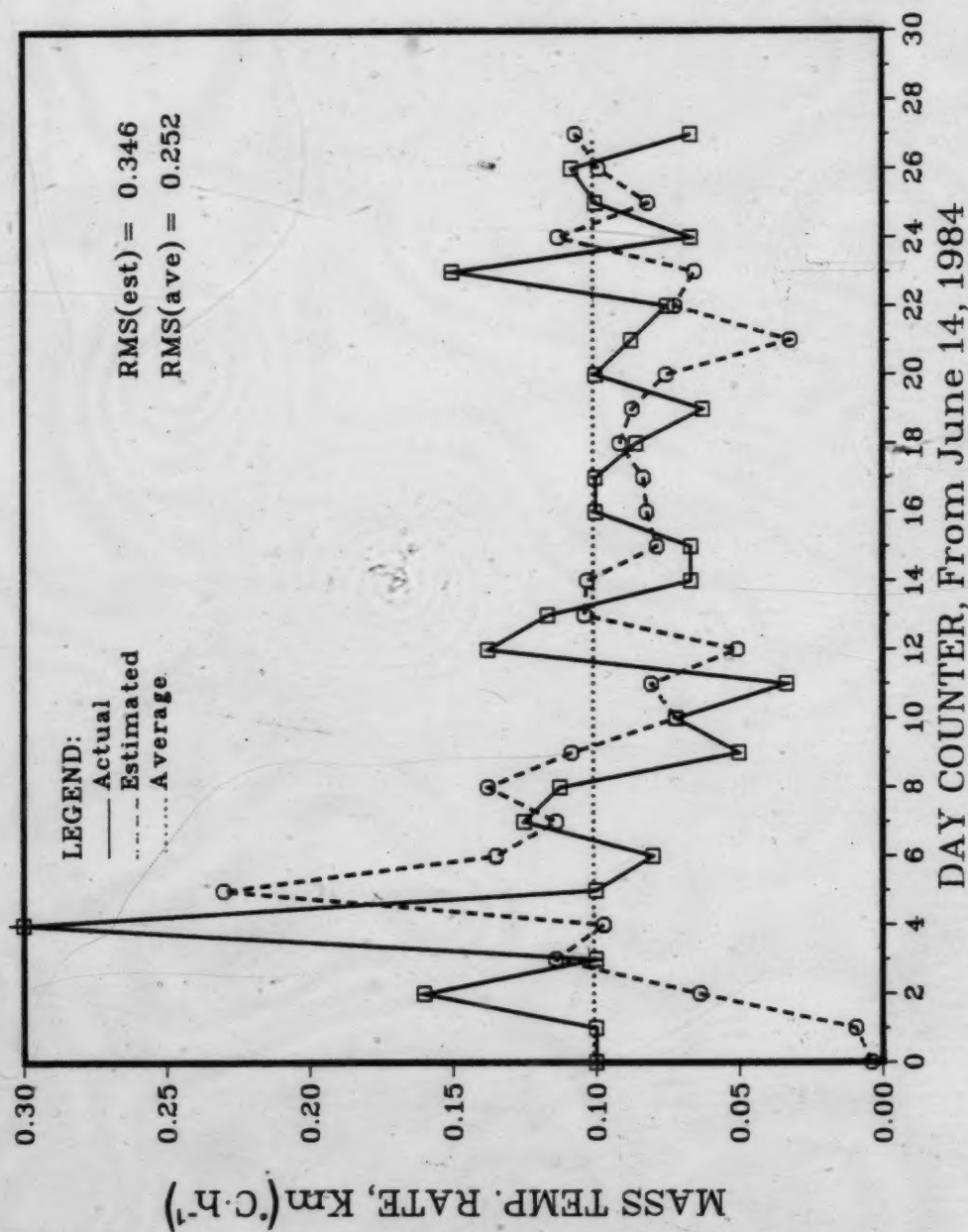


Figure 5.9 A comparison of average, actual, and estimated mass temperature rates over 28 days.

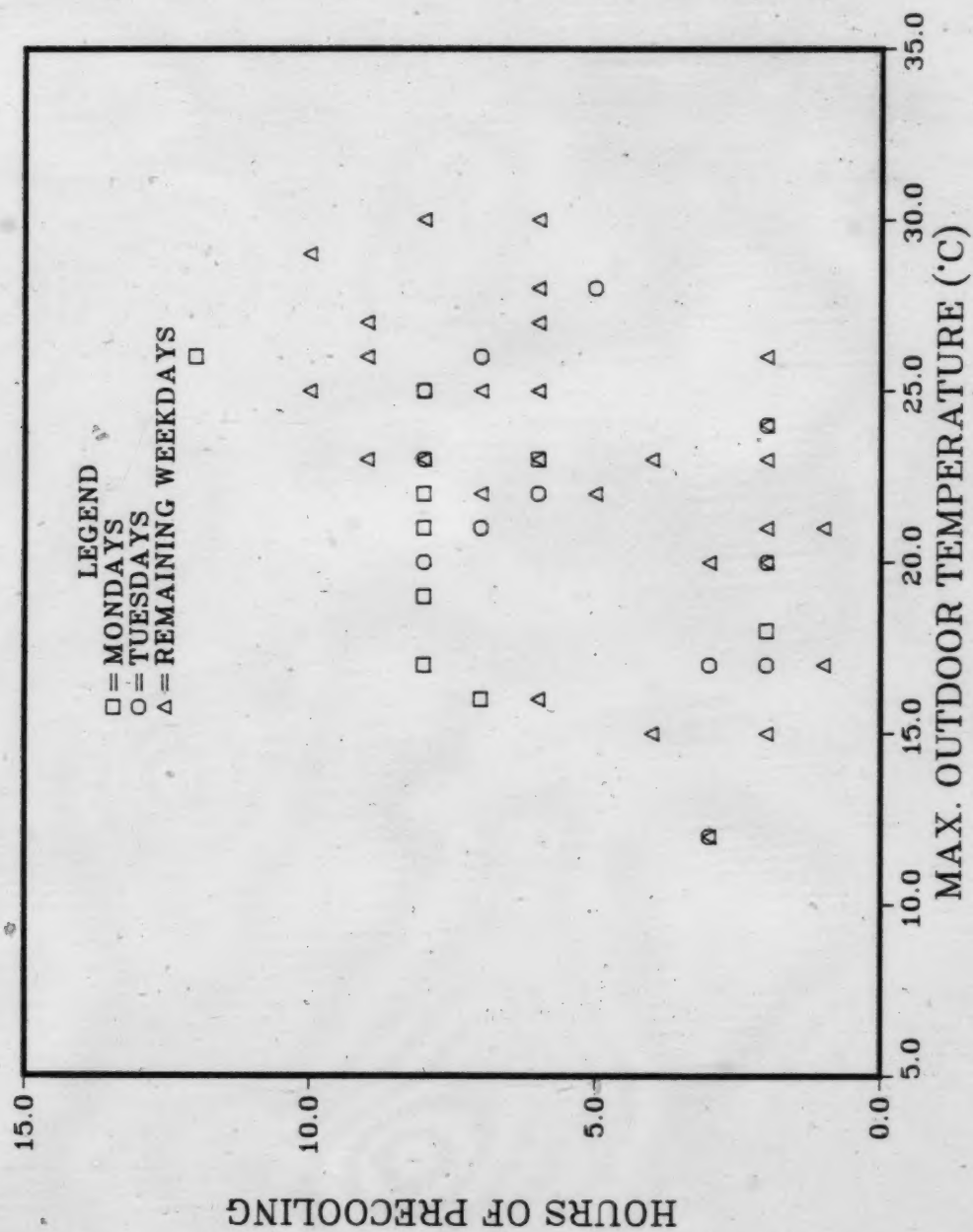


Figure 5.10 Precooling duration as a function of forecasted maximum outdoor temperature.

5.3 Comfort

As noted in Chapter 2, the objective used to develop and implement dynamic control was to have a control system which would minimize energy use, while maintaining occupancy comfort. Therefore, this section will examine how the pilot building's environment was altered, and what the occupants' reaction were to this change.

First, two examples are provided to illustrate typical environment and system responses over a 24 hour period. Figure 5.11 shows a day which included six hours of free cooling. Starting at 6:30, the AHU precooled the Administration Building for one hour. From 7:30 to 9:30, normal operating mode ("N") was enabled, acting as a warmup cycle. At 9:30, all conditions for free-cooling operation ("EC") were met. During the free cooling period, maximum, minimum, and average space temperatures were relatively stable. However, near 14:00, the maximum temperature increased (due to solar radiation exposure) so that normal mode was invoked by 15:30. The 24 hour average outdoor temperature for this day was 9.9°C.

During a warmer day (i.e., average outdoor temperature of 15.7°C), Figure 5.12 shows normal operating mode in operation over most of the occupancy period. In this case, three hours of precooling was employed. At 7:30, all conditions for free cooling were met. However, by 8:30 the outdoor temperature had risen above 18°C. In anticipation of large cooling loads, normal mode was invoked. In the

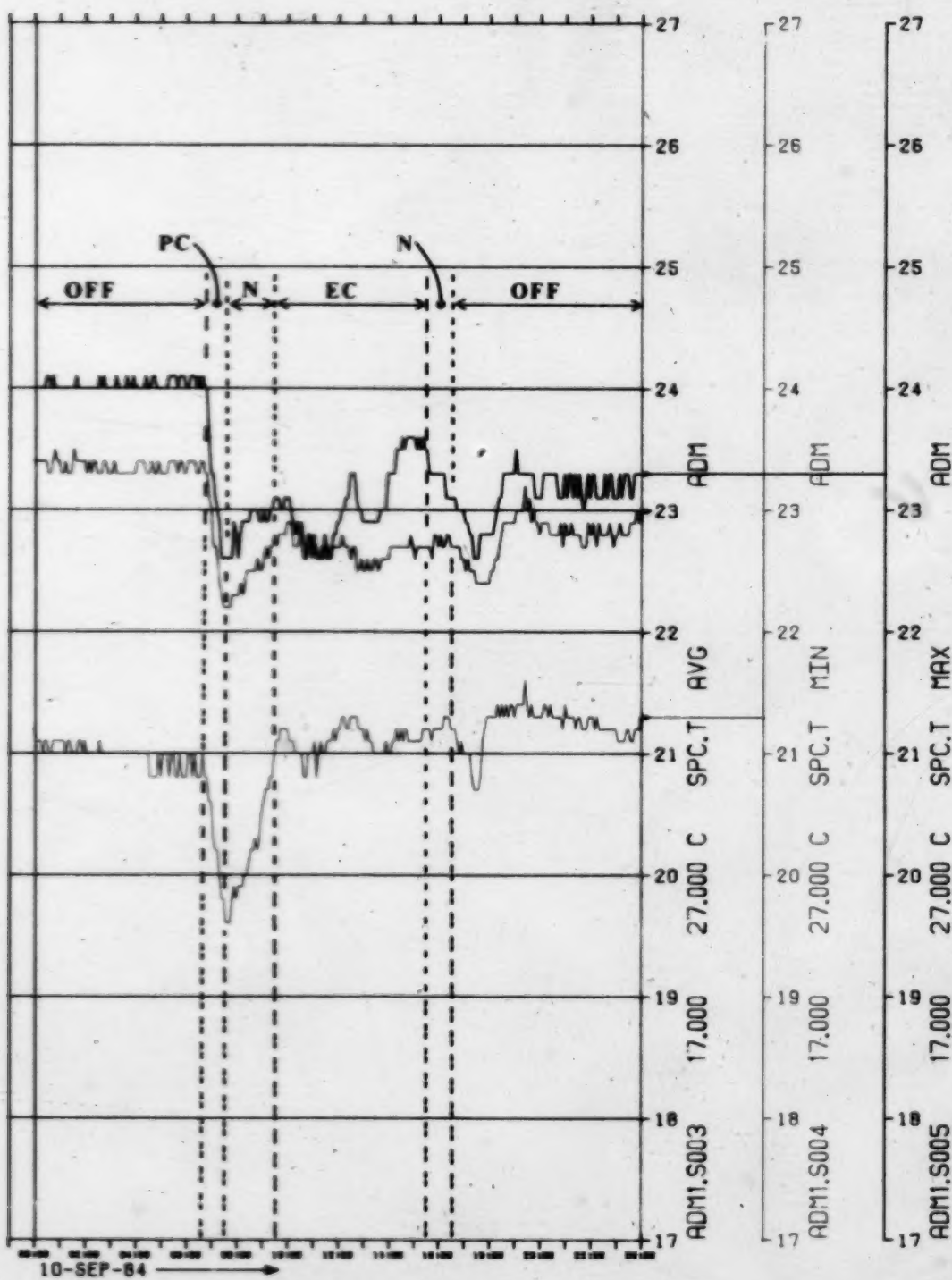


Figure 5.11 Maximum, minimum, and average space temperatures for September 10, 1984.

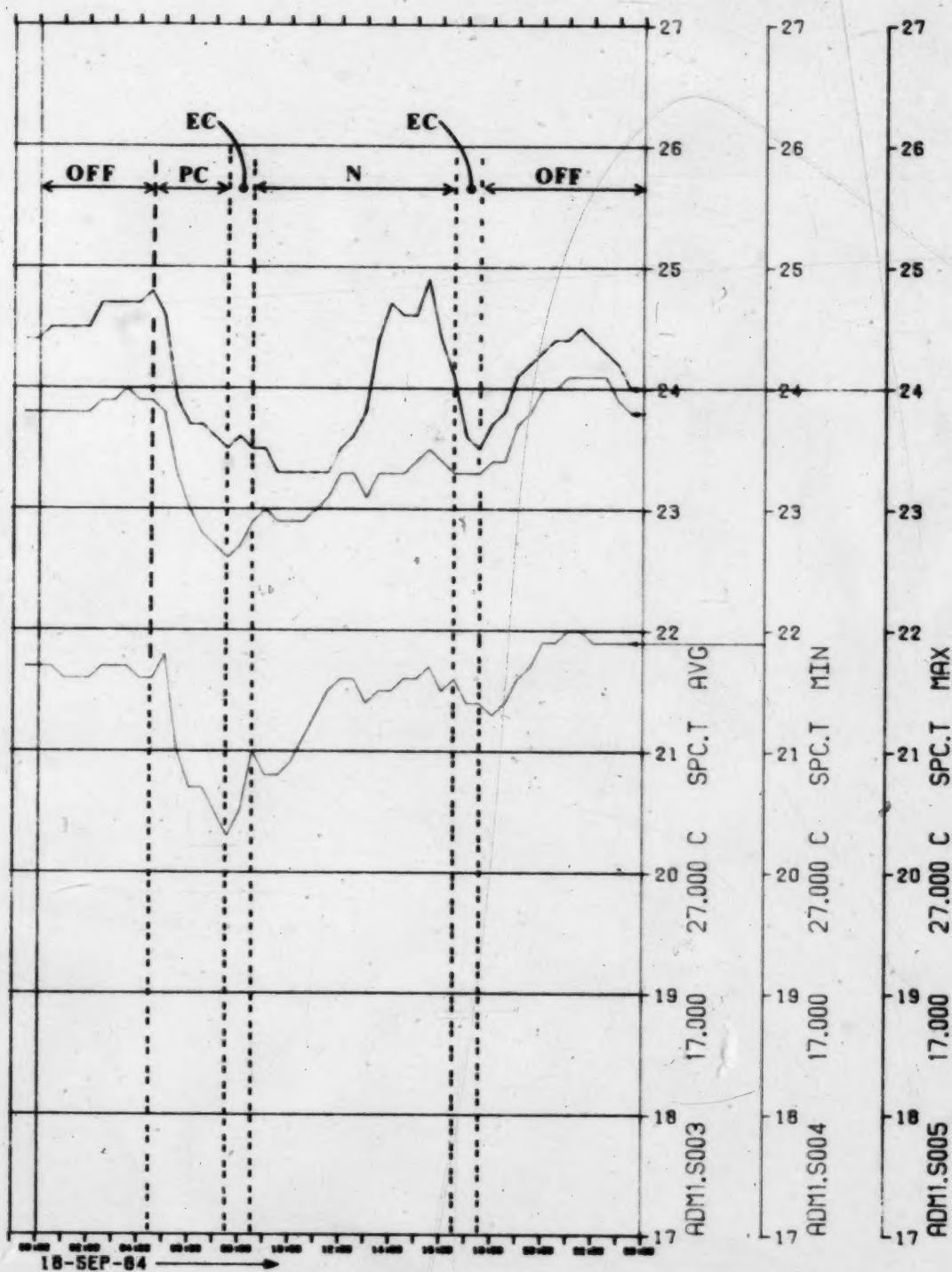


Figure 5.12 Maximum, minimum, and average space temperatures for September 18, 1984.

afternoon, despite the dynamic set point (i.e., S007), the maximum space temperature rose to over 24°C (again due to solar exposure). Later in the afternoon, the maximum space temperature lowered, so that the last hour of operation could be in free-cooling mode.

In comparing these two days of operation, it should be noted that temperature drifting occurred in both free-cooling and normal modes. This was expected since the AHU had not been able to meet cooling loads on warmer days in past years.

To compare how environmental conditions were altered with the installation of dynamic control, two tests were performed--a statistical comparison of space temperatures with and without dynamic control, and an occupant survey (detailed in Appendix A-5).

A statistical comparison of maximum, minimum, and average space temperatures for daytime operation with and without dynamic control was performed by recording these temperatures during two monitoring periods whenever:

1. the outdoor temperature was between 0°C and 15°C, and
2. the real time was between 8:00 and 17:00.

Fifty records of hourly values meeting the above criteria were obtained for both operating strategies. This was achieved in the following manner. For approximately two weeks, hourly space temperatures were recorded with dynamic control in place. Then, another two weeks of monitoring were performed with the operating system switched back to

its previous steady-state operation. This data was arranged in 0.5°C temperature bins to show the distribution of space temperatures with histograms.

Figures 5.13, 5.14, and 5.15 show the average, minimum, and maximum space temperature distributions (respectively) which existed with and without dynamic control. All three graphs show there is a greater distribution of temperatures when using dynamic control. This would suggest that the Administration Building AHU cannot maintain the same level of zone control when using dynamic control. However, this does not necessarily imply that comfort is reduced. For example, maximum space temperatures were reduced with dynamic control.

Perhaps the best measure of dynamic control's effect on the environment is from occupant feedback. The questionnaire in Appendix A-5 was distributed by the office manager of the Administration Building. A 100% response was achieved, excluding those individuals who were not in the building during the periods indicated on the questionnaire.

Figure 5.16 summarizes the results of the questionnaire. The respondents who filled out the "Don't know" category had moved to a different location within the building between or during the queried periods. Excluding these, 84% felt there has either been no change or an improvement in comfort compared to operation without dynamic control. Those who felt comfort conditions were less acceptable mostly complained about being too cold. As

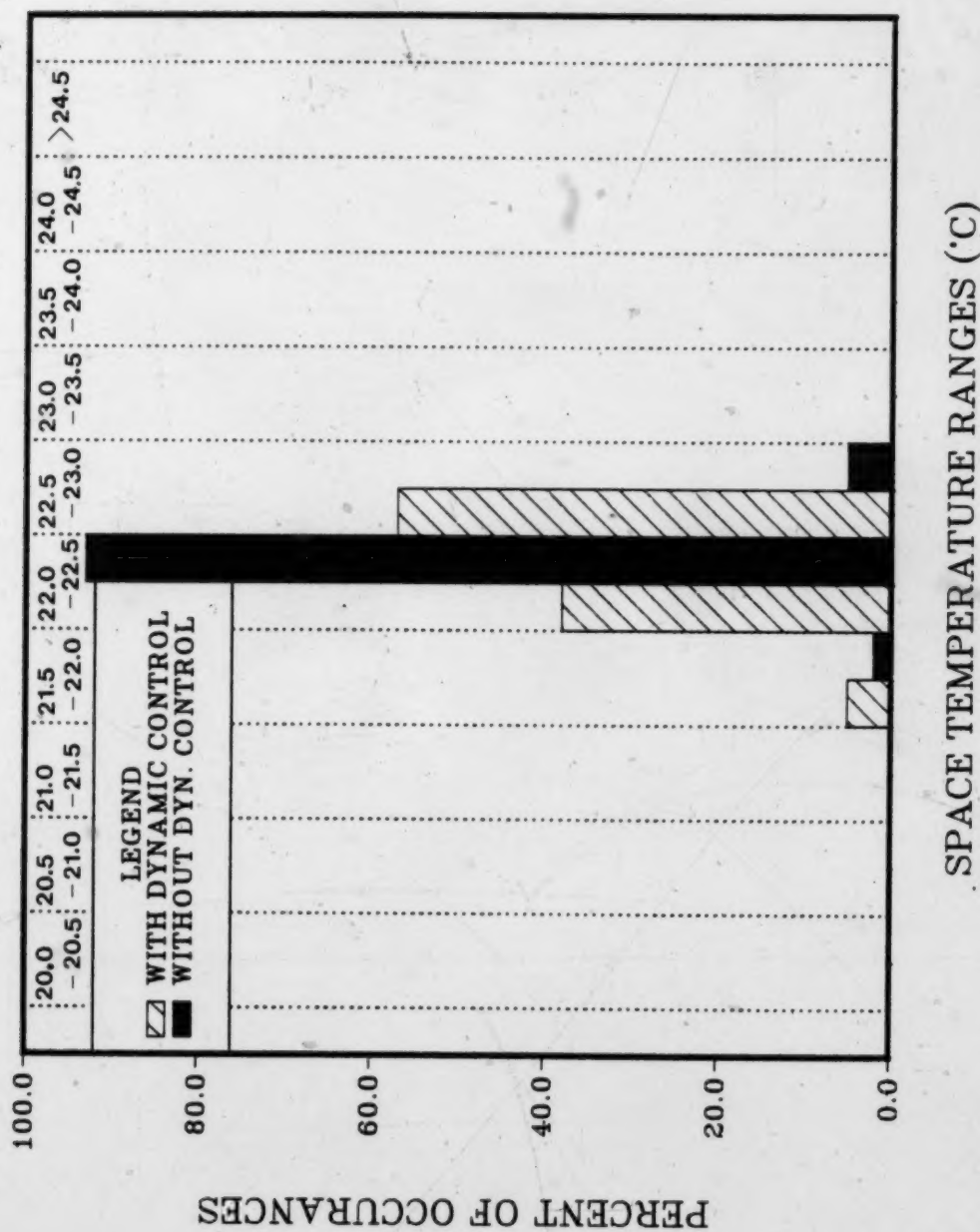


Figure 5.13 Distribution of average space temperatures with and without dynamic control.

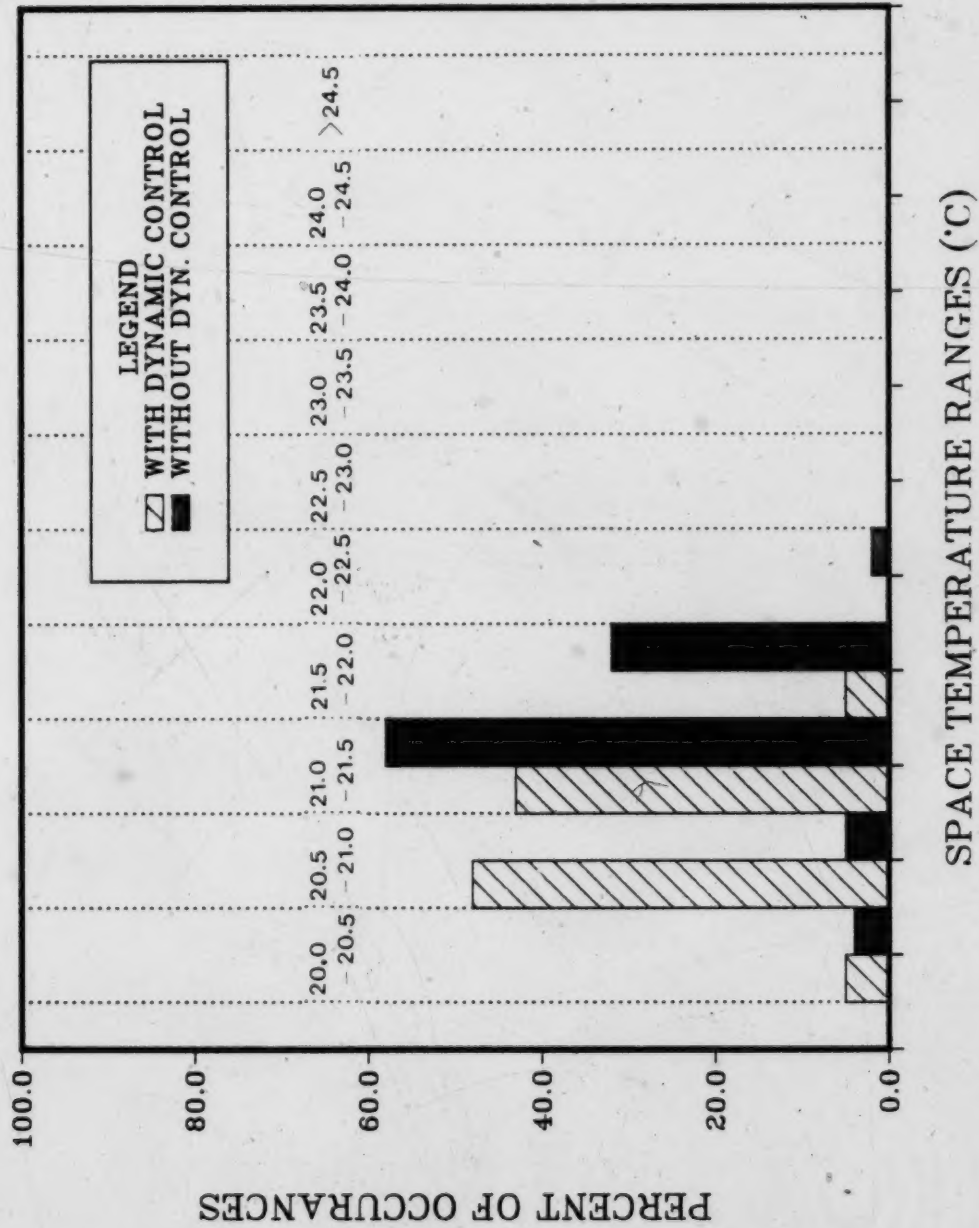


Figure 5.14 Distribution of minimum space temperatures with and without dynamic control.

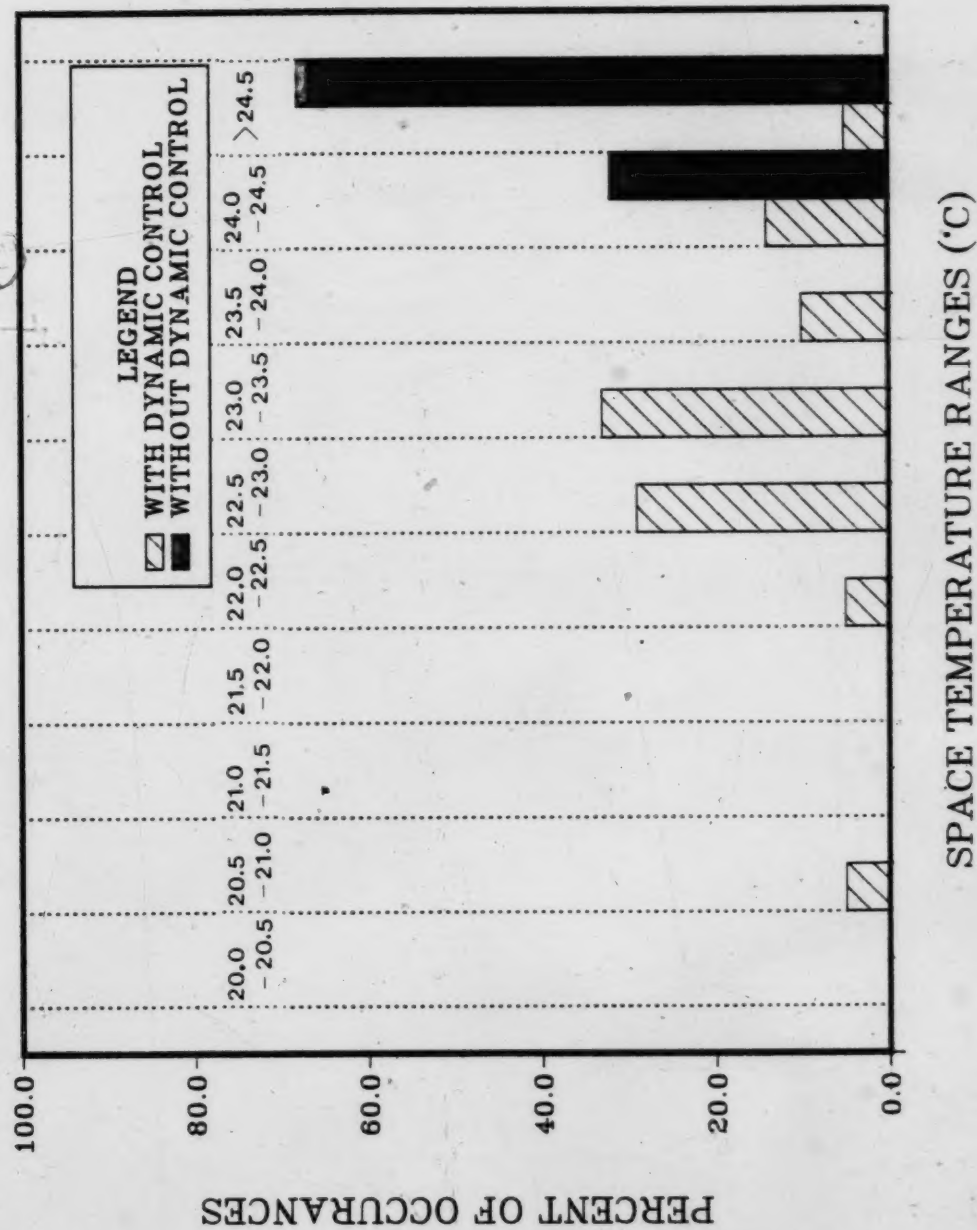


Figure 5.15 Distribution of maximum space temperatures with and without dynamic control.

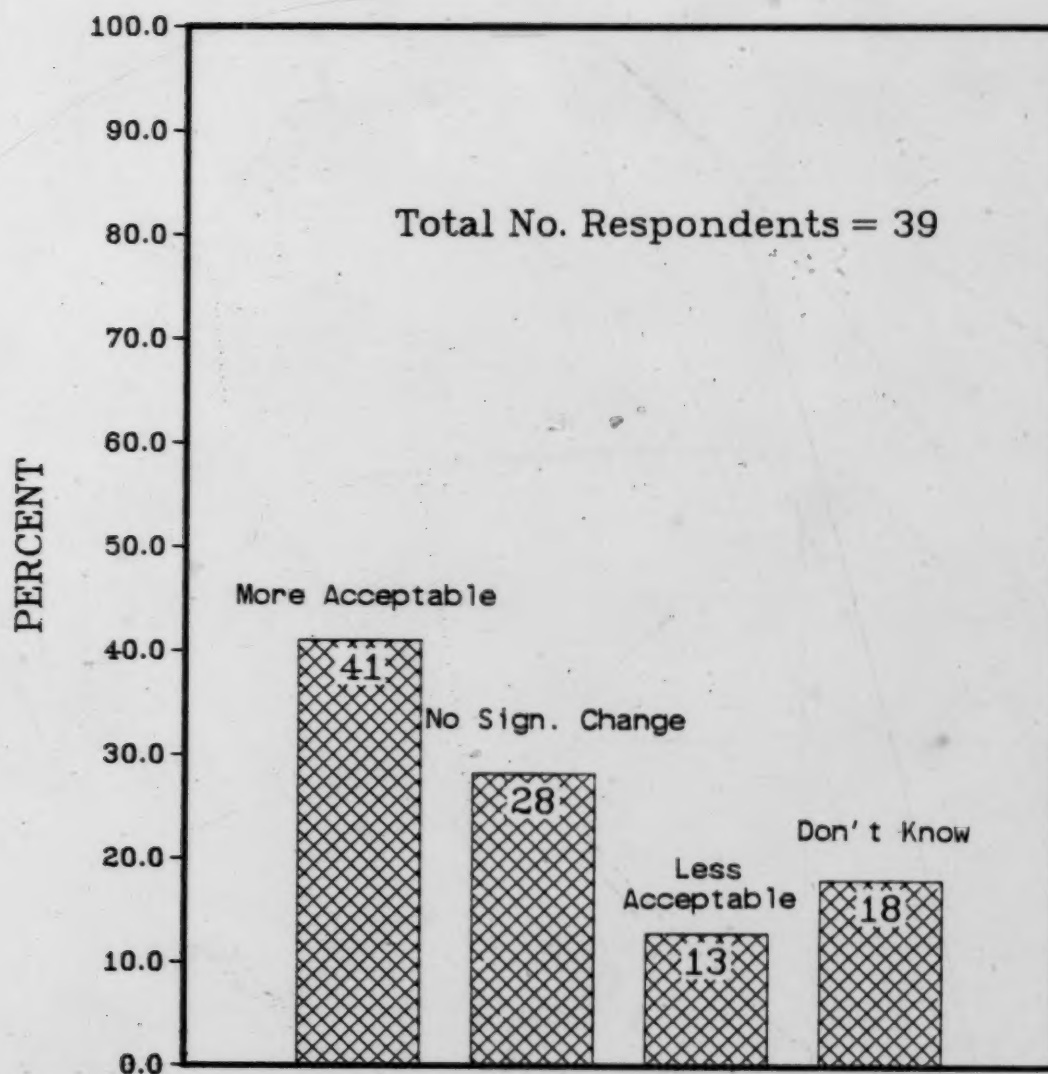


Figure 5.16 Results of the occupant questionnaire.

Figures 5.13 and 5.14 indicate, space temperatures were indeed lowered with the use of dynamic control. However, at the same time, the 41 percent who felt there was an improvement most likely gave this response because of these lowered temperatures.

5.4 Energy and Other Resources

Given that thermal comfort was found to be acceptable (by the majority), it would be useful to examine (1) how the pilot installation altered energy use within the building and (2) what resources were invested to complete the implementation.

The influence which dynamic control had on the Administration Building's energy consumption was unclear at the termination of monitoring. This was due to the short time frame involved and the absence of past chilled water usage measurements (required to establish a base line). Nevertheless, a limited analysis was performed, first using total consumption data, then using calculated HVAC data.

Figure 5.17 shows the monthly total steam consumption during the summer months of 1983 and 1984. Steam values have been normalized by dividing by the number of heating degree-days (16°C base) for each month. Steam consumption was greater under dynamic control (i.e., 1984 period) for the months of June and July, but less for August.

With gross electric consumption, the trend was reversed. That is, electric power usage was less in 1984

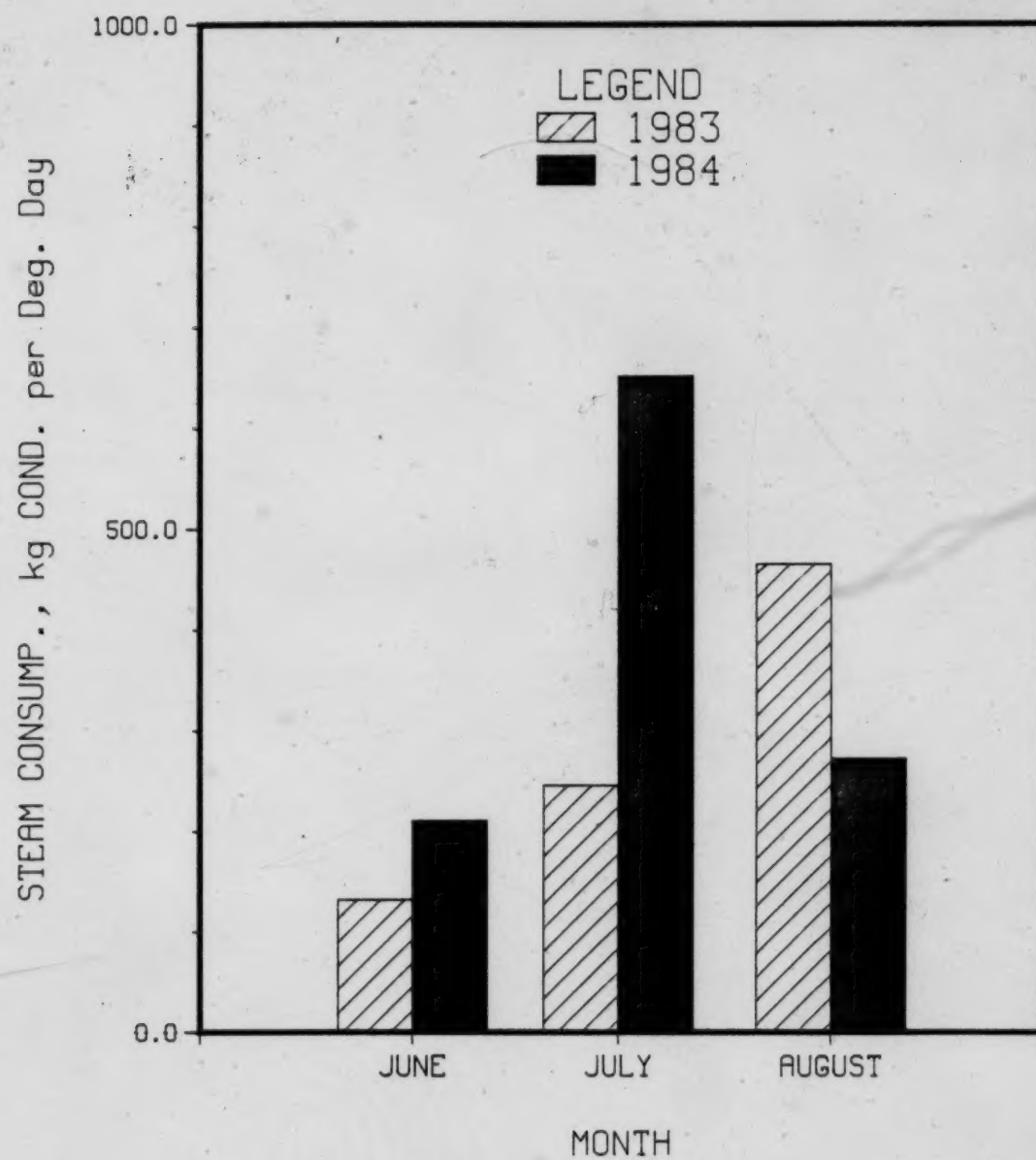


Figure 5.17 A comparison of monthly gross steam consumption for years 1983 and 1984.

for the month of June, but greater for July and August. (See Figure 5.18.) However, there can be little confidence in relating these values to dynamic control's effect on consumption since service pumps and fans only make up 13% of the total electric load³⁰.

A second attempt to quantify the influence of dynamic control on energy use was made by monitoring variables which affected HVAC energy consumption on a weekly basis. In addition, metered values of chilled water volume, electric energy, and steam condensation were recorded. This was done over a period of seven weeks with dynamic control operation. Then, for one week, the HVAC system was converted back to its original strategy, with the same monitoring procedure repeated.

The results of this weekly analysis are plotted in Figure 5.19. Chilled water (CHW), electrical power (ELEC), and steam (STM) consumption with dynamic control are plotted with best-fit curves against cooling degree-hours per week (16°C base). The single measures of energy use without dynamic control (at $1.0^{\circ}\text{C}\cdot\text{h}/\text{week}$) are shown in lower-case lettering. In comparing usage with and without dynamic control, this plot indicates that dynamic control uses less steam, more chilled water, and about the same amount of electricity than operation without dynamic control, for the $1.0^{\circ}\text{C}\cdot\text{h}/\text{week}$ level. However, there can be little confidence in this observation reflecting any general patterns, since

³⁰ See Table 4.2a for a breakdown of electric use in the Administration Building.

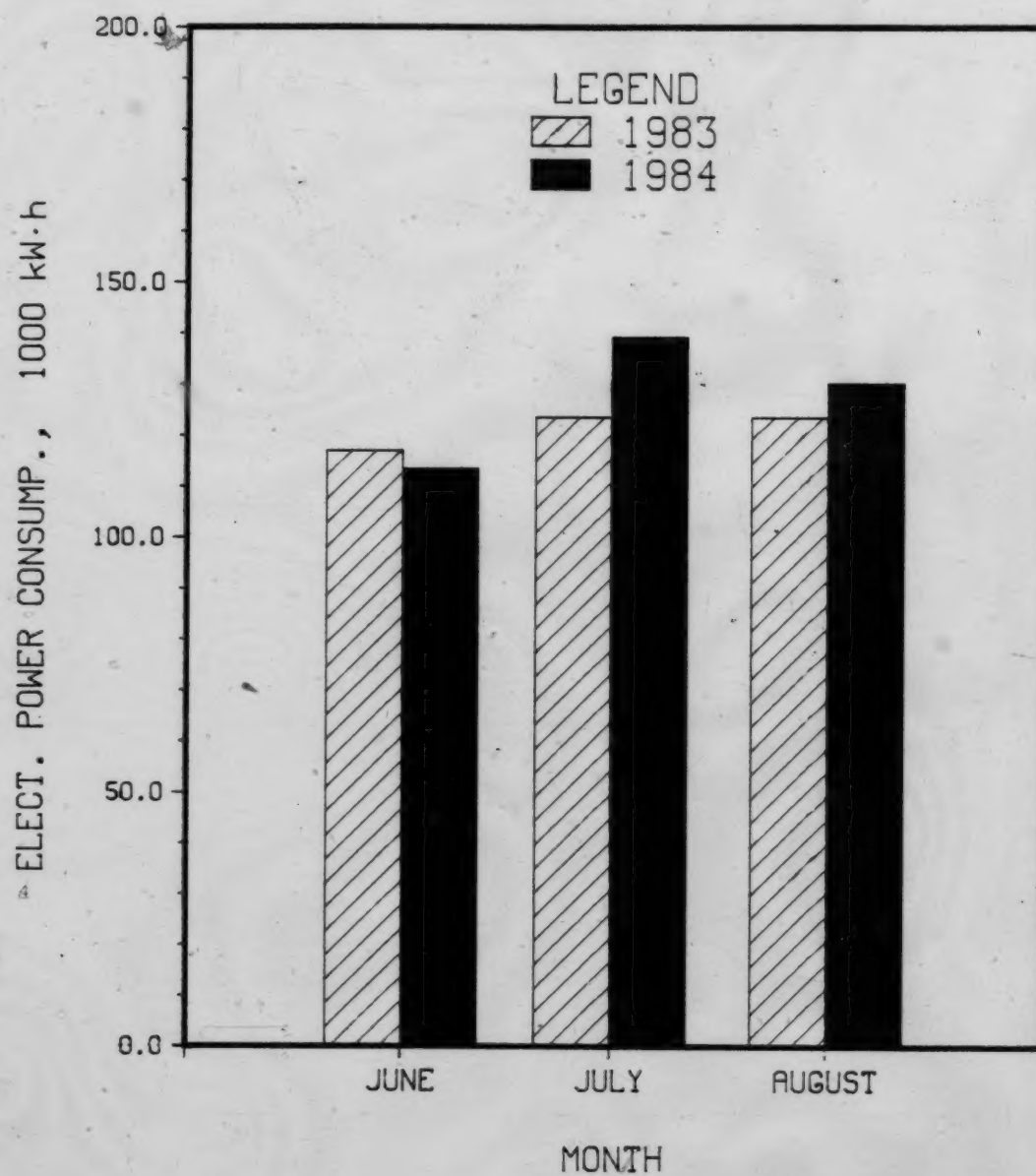


Figure 5.18 A comparison of monthly gross electric power consumption for years 1983 and 1984.

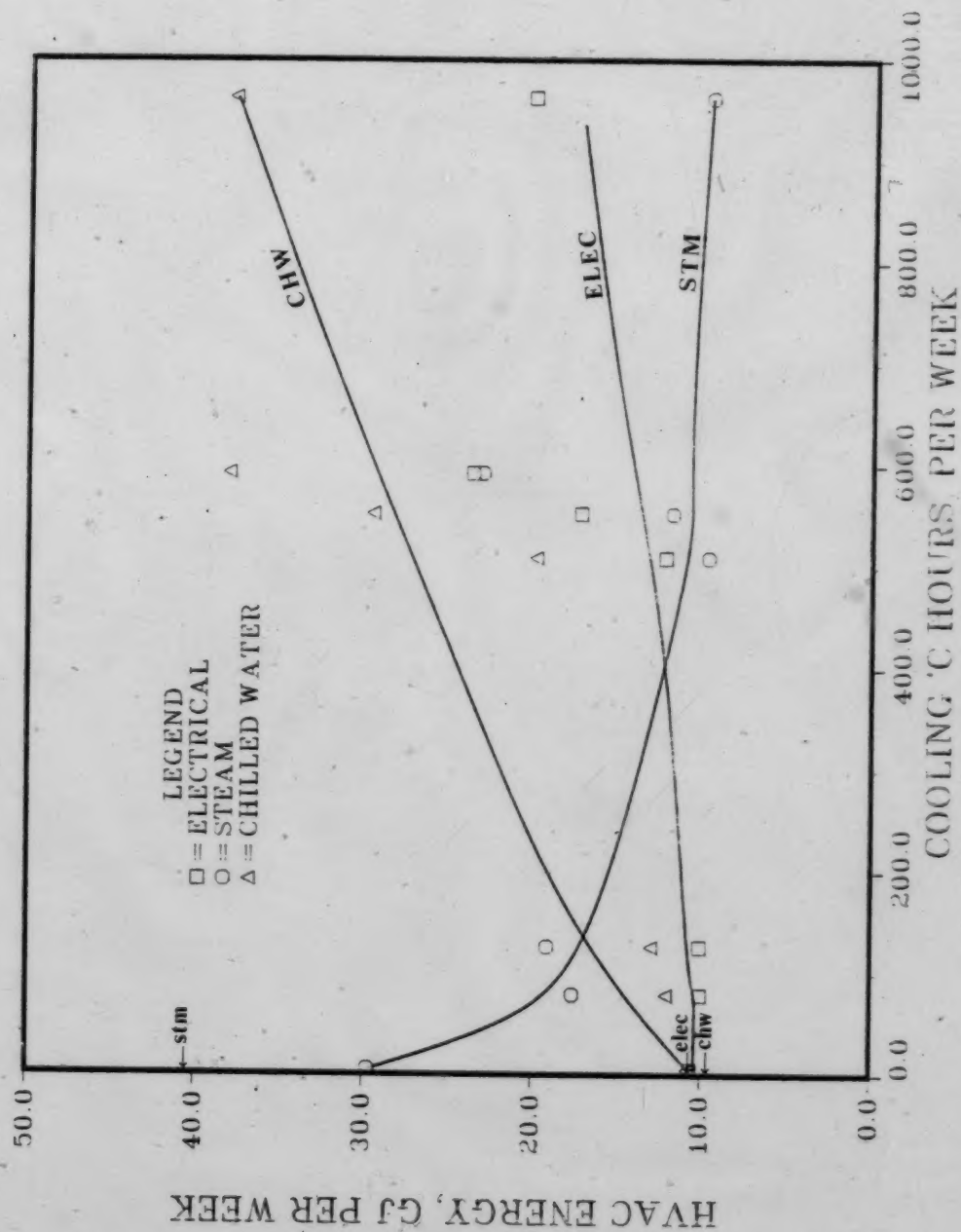


Figure 5.19 Weekly energy consumption, with dynamic control (upper case) and without dynamic control (lower case).

(1) only one point has been considered, and (2) the confidence limits for the two data sets are unknown. It is therefore apparent that a longer evaluation period is required to determine dynamic control's effect on consumption levels.

As noted in Section 4.2, the resources which were required to implement the pilot project included a few mechanical alterations (i.e., two thermocouples and one pyranometer) and a significant amount of software revision. Manpower requirements were documented during the study, and are summarized in Table 5.1.

In considering future installations of dynamic control, the University estimates that manpower requirements could be reduced from 16.5 man-months to less than three man-months (i.e., a 67% reduction) for each existing building. This is because a large portion of work covered in this study would not have to be repeated. Hardware requirements will depend on the existing state of the building control system, and the type of building being considered.

Table 5.1 Manpower requirements for the pilot project.

Item	Man months
Theoretical development	5.0
Energy audit	0.5
Software development	3.0
Strategy implementation & troubleshooting	4.0
Education of staff & occupants	0.5
Documentation	1.0
Evaluation	2.5
Total	16.5

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The general strategy developed for dynamic control coupled with the specific results of the pilot project has led to several conclusions. These will be discussed as follows:

1. Free-cooling operation.
2. Precooling operation.
3. Comfort and energy.

Free-cooling operation. The objective of dynamic control is the maximization of periods during which a conditioning system's thermal inputs can be disabled. These "free-cooling" periods can be applied only during a specific outdoor enthalpic range. This range can be enlarged by temperature drifting. Conversely, zone variations, room air distribution imperfections and load variations will diminish this range.

For the building studied, the effective balance temperature range was found to be approximately 4°C to 22°C. During these periods, total energy consumption is less than any other operational mode. However, the system's ability to address zone variations is eliminated during free cooling, so that interior space temperature variations are greater when compared to normal operation.

Precooling operation. A major challenge in any dynamic control strategy development is to determine how to control

the thermal mass of the structure so that durations of free cooling are augmented and total energy expenditure is minimized. This is a complex problem since the storage medium is not confined to a separate location, but rather involves the entire building mass. For the building studied, the loss of zone control during free cooling and the required comfort constraints disallowed any daytime thermal manipulation strategies. However, preoccupancy precooling was possible.

Results suggest that associated algorithms can be greatly simplified by determining which variables most significantly affect the cooling load and by establishing an average mass temperature reading to represent thermal storage effects. The final precooling algorithm developed for the pilot building was based on the current mass temperature and the next day's forecasted maximum temperature. Outdoor temperature and solar radiation forecasts based on deterministic models were acceptable for the control of the building. However, other structures with large fenestration cooling loads may require more accurate solar and temperature prediction models.

Comfort and energy. Dynamic control offers less space temperature control than normal (i.e., steady-state) control. The loss of local control of zone variations produces a larger spread of space temperatures within a building. However, in the building studied, comfort conditions improved with dynamic control because maximum

space temperatures were reduced.

Energy savings associated with the installation of dynamic control have not yet been quantified. This was due to the limited duration of monitoring after implementation. Nevertheless, it is logical that savings are incurred during free cooling, since no thermal energy is being consumed. However, the effect of dynamic control on energy consumption also depends on the precooling strategy employed.

6.2 Recommendations

The following recommendations have been identified at the conclusion of this study.

1. Field monitoring should be continued to establish the effectiveness and energy saving potential of free cooling, particularly for outdoor temperatures below 10°C.
2. Further study of short term forecasting using adaptive techniques could help improve the accuracy of load predictions.
3. A variable shutdown period could be integrated with the existing facility to further reduce energy use.
4. Strategies employed in the pilot study were catered to the specific characteristics of the building. Further insight into dynamic control could be obtained by developing and monitoring systems for buildings of differing nature.

REFERENCES

- Asher, R. B., Andrisani II, D., & Dorato, P. Bibliography on adaptive control systems. *Proceedings of the IEEE*, 1976, 64(8), 1226-1227.
- ASHRAE *ASHRAE Handbook: 1981 Fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1982.
- Berglund, L., & Gonzalez, R. Application of acceptable temperature drifts. *ASHRAE Transactions*, 1978, 84(1), 110-121.
- Box, G. E., & Jenkins, G. M. *Time Series Analysis, Forecasting and Control*. San Francisco: Holden-Day Inc., 1976.
- Brown, G. Simulation by digital computer program of the temperature variation in a room. In T. Kusuda (Ed.), *Use of Computers for Environmental Engineering Related to Buildings* (U.S. Dept. of Commerce Building Series No. 39). Washington, D.C.: U.S. Government Printing Office, 1971.
- Catani, M. J., & Goodwin, S. E. Heavy building envelopes and dynamic thermal response. *Journal of the American Concrete Institute*, 1976, 73(2), 85.
- Duffie, J., & Beckman, W. *Solar Energy Thermal Processes*. New York: John Wiley and Sons, 1974.
- Fisk, D. J. *Thermal Control of Buildings*. Englewood, N.J.: Applied Science Publishers Ltd., 1981.
- Fassbender, H. W. Centralized energy management systems for commercial and industrial buildings. In J. P. Millhone, & E. H. Willis (Eds.), *New Energy Conservation Technologies and Their Commercialization* (Vol. 2). New York: Springer-Verlag, 1981.
- Forrester, J. R., & Wepfer, W. J. Formulation of a load prediction algorithm for a large commercial building. *ASHRAE Transactions*, 1984, 90(2).
- Givoni, B. Heat storage in buildings: an overview. In C. J. Hoogenboorn, & N. H. Afgan (Eds.), *Energy Conservation In Heating, Cooling, and Ventilating Buildings* (Vol. 2). Washington, D.C.: Hemisphere Publishing Corp., 1978.
- Griffiths, T. D., & McIntyre, D. Sensitivity to temporal

variations. *Ergonomics*, 1974, 17, 499-507.

Gupta, C. L. A systems model for environmental design of buildings. In T. Kusuda (Ed.), *Use of Computers for Environmental Engineering Related to Buildings* (U.S. Department of Commerce Building Science Series No. 39). Washington, D.C.: U.S. Government Printing Office, 1971.

Hartman, T. "Dynamic control" of heat called key to saving energy. *Air Conditioning Heating and Refrigerating News*, 1980, 151(1), 14-16.

Hittle, D. C. Calculating building heating and cooling loads using the frequency response of multilayered slabs. (Doctoral dissertation, University of Illinois, 1981). Michigan: University Microfilms International, 1983.

Holmes, W. A. An energy management case study of the Quinto Consulting Center, a comprehensive mental health center in Columbus, Indiana. *Energy Engineering*, 1983, 80(6).

Kamimura, K. Application of optimization control to air conditioning: operation and algorithm of the optimum start/stop programmer (OSSP). *Energy Developments in Japan*, 1982, 4, 261-281 (Japan).

Kimura, K. I. *Scientific Basis of Air Conditioning*. London: Applied Science Publishers Ltd., 1977.

Kline, W. A. An evaluation of dynamic data system modelling for the characterization and forecasting of time series. (M.S. thesis, University of Illinois, 1979).

Lock, G. H. *Heat Transfer Theory, a unified introduction to its structure, scope and technique*. Edmonton, Alberta: Department of Mechanical Engineering, University of Alberta, 1984.

McQuiston, F. C., & Parker, J. D. *Heating, Ventilating, and Air Conditioning Analysis and Design*. New York: John Wiley and Sons, 1977.

Muncey, R. W. R. *Heat Transfer Calculations for Buildings*. London: Applied Science Publishers Ltd., 1979.

National Concrete and Masonry Association. Energy conservation with masonry. *TEK Bulletin No. 58*. McLean, Virginia: Author, 1974.

Perkins, D. Heat balance studies for optimizing passive cooling with ventilation air. *ASHRAE Journal*, 1984, 26(2), 27-29.

Portland Cement Association. *The Concrete Approach to Energy Conservation*. Skokie, Illinois: Author, 1974.

Ranieri, M. A. Characteristics of different sizes and types of intelligent control systems. *ASHRAE Transactions*, 1982, 88(1), 1229-1236.

Shavit, G. Design and control strategies for energy storage. *ASHRAE Transactions*, 1980, 86(2), 631-645 (Discussion).

Sprague, C. H., & McNall, P. E. The effects of fluctuating temperature and relative humidity on the thermal sensation of sedentary subjects. *ASHRAE Transactions*, 1970, 76(1), 146-156.

Wolsey, W. H. *Basic Principles of Automatic Control, with special reference to heating and air conditioning systems*. London: Hutchison Educational Ltd., 1975.

**APPENDIX A-1: Administration Building Single-Line Air
Schematics**

The following figures show the single-line air schematics for each level of the Administration Building, as observed just before implementation of the pilot project. In addition, the air-conditioning cabinets (marked "A/C"), RCMS thermocouple locations (for space temperature measurement), and east/west zone divisions for the main AHU are indicated.

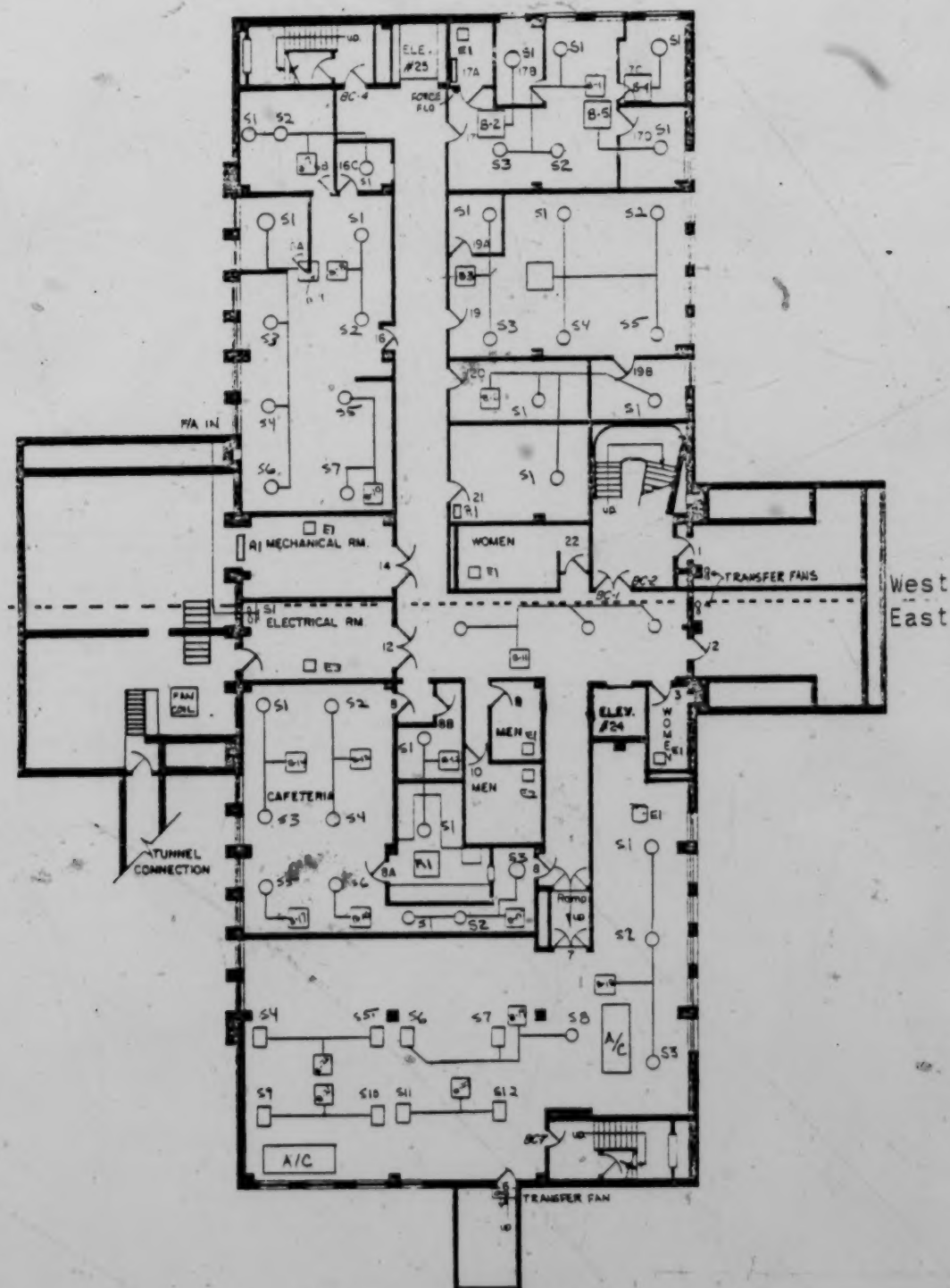


Figure A-1.1 Basement air-line schematic.

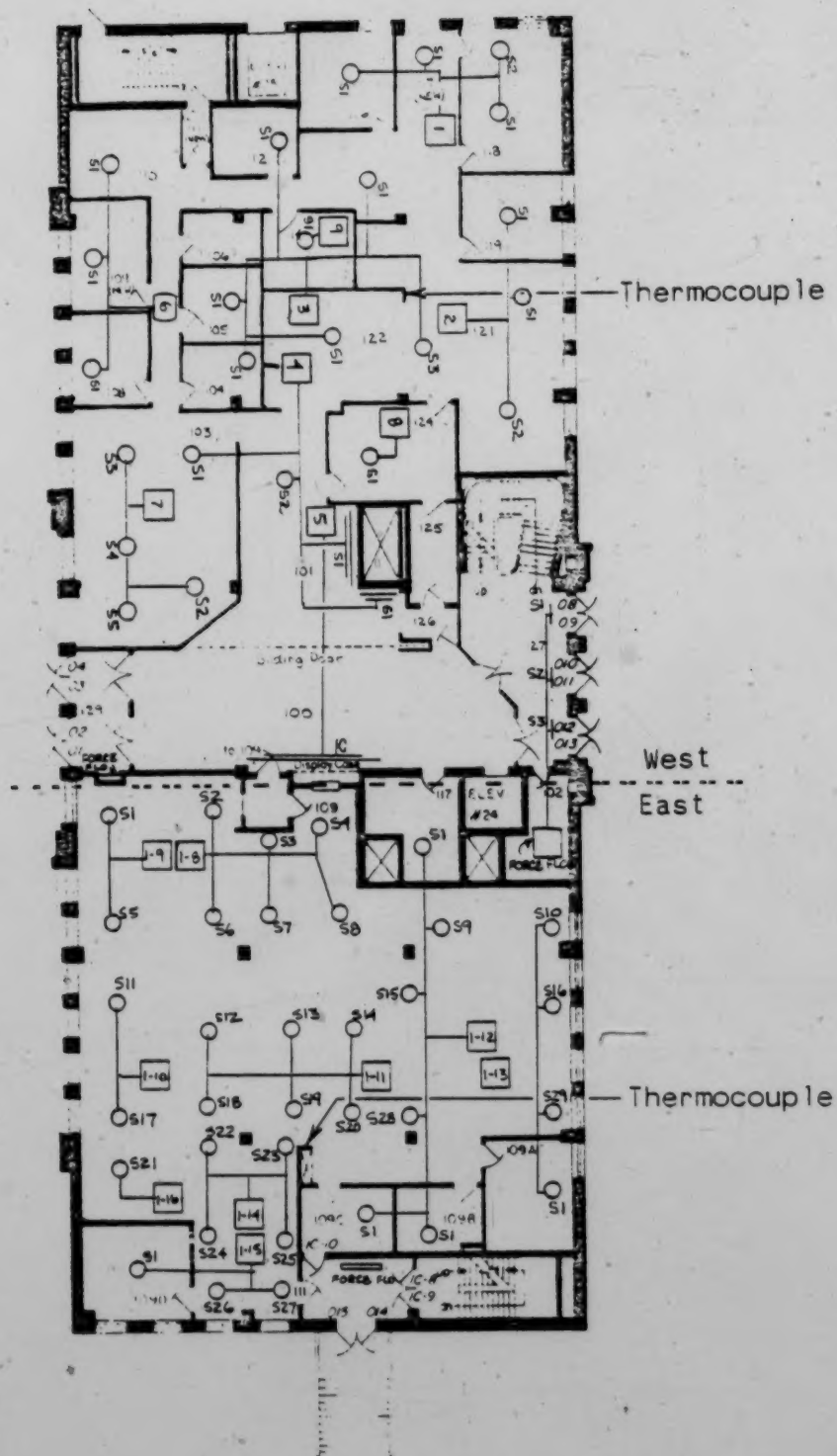


Figure A-1.2 First floor air-line schematic.

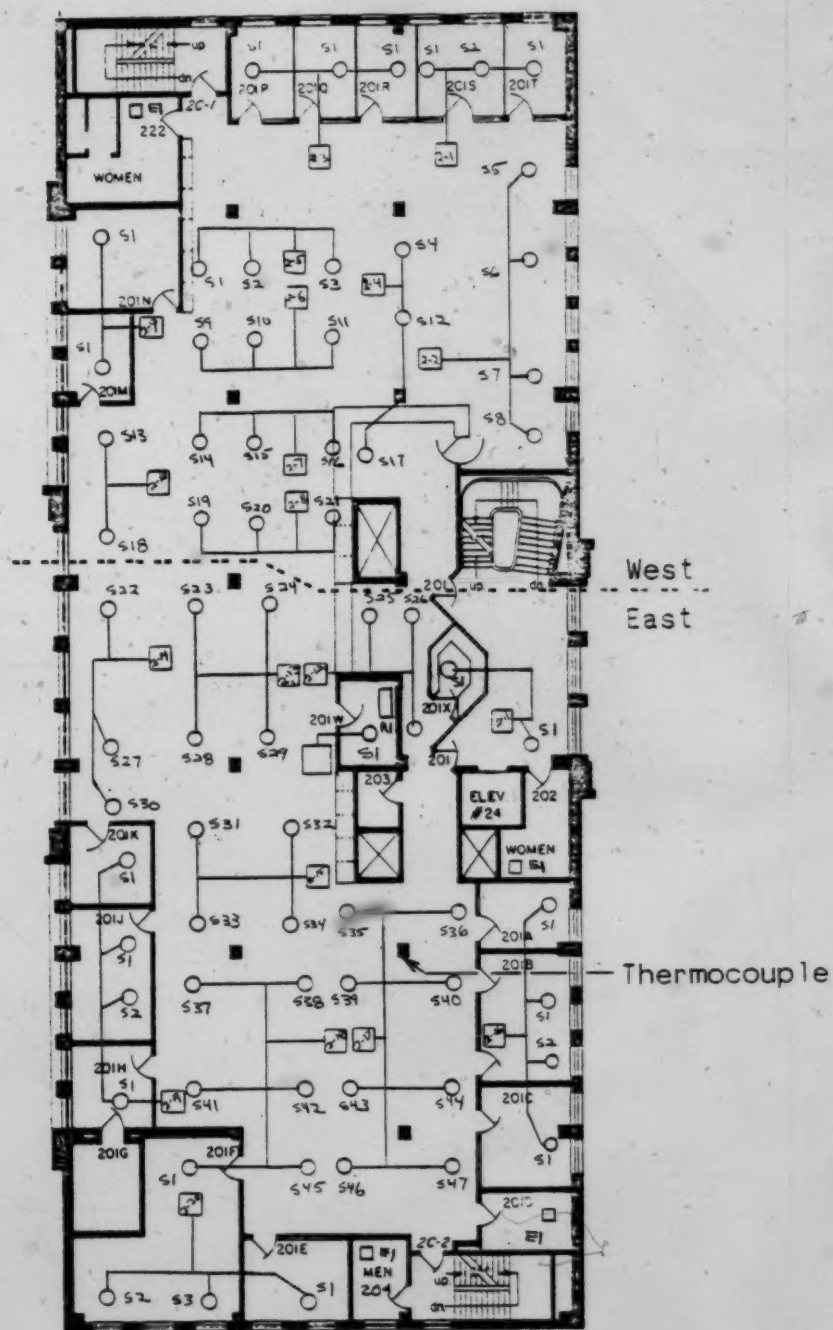


Figure A-1.3^u Second floor air-line schematic.

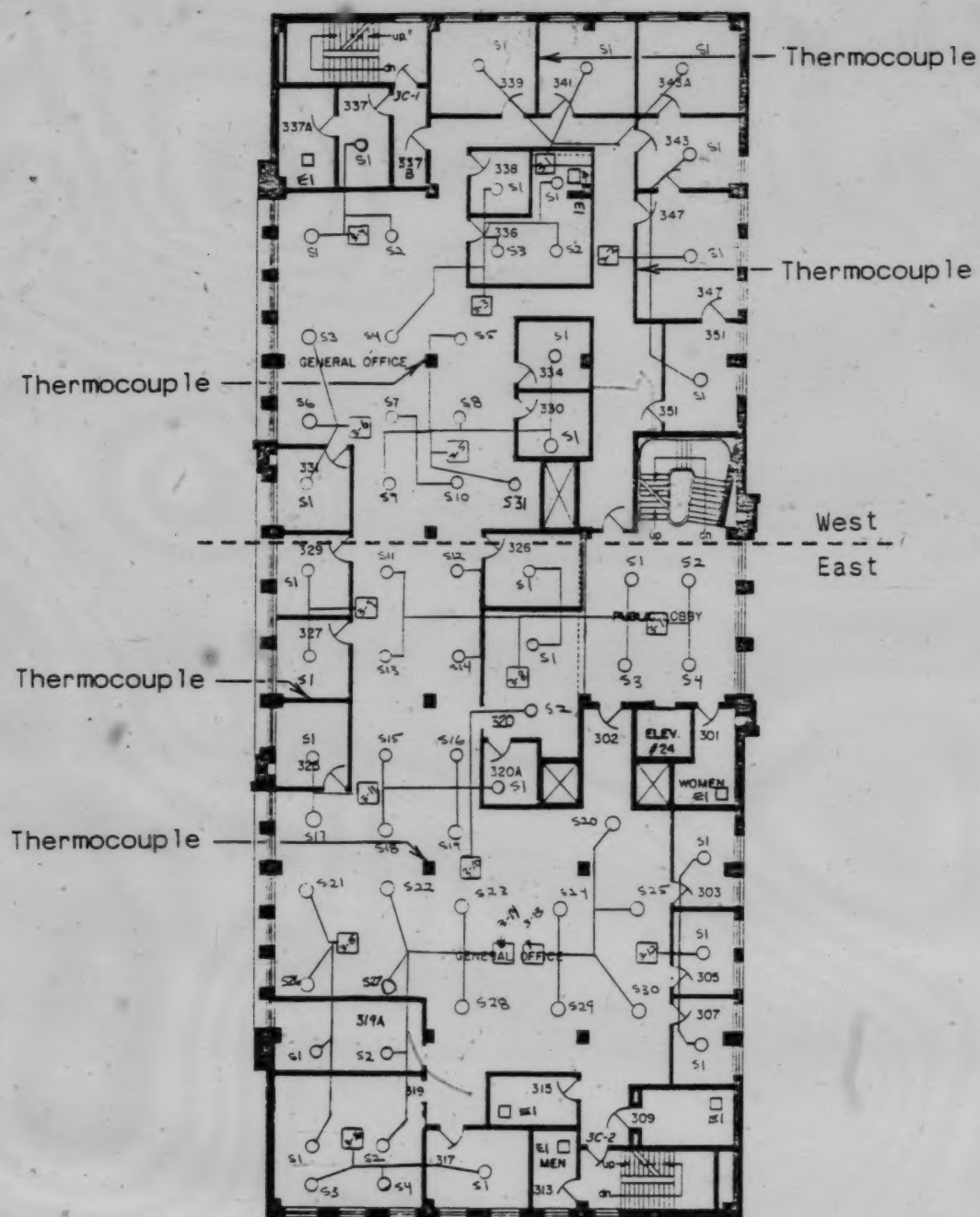


Figure A-1.4. Third floor air-line schematic.



Figure A-1.5 Penthouse floor air-line schematic.

APPENDIX A-2: Energy Audit of the Administration Building

Energy analysis of the pilot building was divided into two main categories, namely:

1. electrical power, and
2. steam heating.

No records of chilled water consumption were available.

Gross annual electric power consumption over the past nine years is listed in Table A-2.1. For monthly records, the eight year average equals $102.7 \times 10^3 \text{ kW} \cdot \text{h/month}$. The composition of this power load was determined through analysis of plans and on-site surveys, and is summarized in Table A-2.2. Details dealing specifically with appliances (i.e., office and kitchen) are given in Table A-2.3

Table A-2.4 lists the gross steam consumption for the Administration Building since 1976. Monthly records were found to follow the same pattern each year. That is, consumption was greatest for the winter months, and least during the summer. This is shown in Table A-2.5.

To determine the portion of steam heating used for domestic hot water (DHW), an estimate of the volume of DHW was made. Then, a heat transfer analysis was performed, using measured temperatures (e.g., inlet and end-use outlets). Converter gain (assumed constant over the year) was calculated to be 10.1 GJ/month , with parasitic loss assumed equal to 1.4 GJ/month .

The portion of steam heating applied to space heating was calculated by assuming that August steam consumption did

not include significant use of humidity control. That is,

$$(\text{Est'd. space htg. in Aug.}) = (\text{gross con.}) - (\text{DHW con.})$$

Table A-2.1 Total power consumption.

Year	Cumulative Consumption Apr. to Mar. (1000 kW)	% Increase (+) or Decrease (-)
1975	1047.89	
1976	1037.40	- 1.0
1977	935.39	- 2.8
1978	1032.00	+10.3
1979	1177.80	+14.1
1980	1213.80	+ 3.1
1981	1615.91	+33.1
1982	1795.20	+11.1
1983	1487.40	-17.1

Table A-2.2 Electric load data.

Load	Total Capacity (kW)	Diversity Factors Time Period	Factor	Estimated Consump. (1000 kW h/mo)	Fraction of Total Load in 1982/1983	Comments
Lighting	57.9	Mon-Fri, 7-8, 16-17 Mon-Fri 8-16 All other	0.80 0.94 0.10	15.12	0.10	
Pumps	7.1	Mon-Fri 7-17 All other	0.80 0.45	2.94	0.02	
Fans	51.2	Mon-Fri 4-20 All other	0.80 0.05	16.0	0.11	
Elevators	37.0	Mon-Fri 7-17 All other	0.30 0.01	3.2	0.02	
Office	7.0	See Table A-2.3	--	1.3	0.01	Includes kitchen appliances; excludes computing facilities
Computing	Unknown	Mon-Fri 8-16	1.00	111.0	0.74	Includes CPU, disk controller, tape drives, printers & CRTs
Totals				149.6	1.00	

Table A-2.3 Appliance power data..

Appliance	Quantity	kW/Appl.	Daytime Diversity Factor	Daytime Unit Load (kW)
Typewriter	80	0.075	0.60	3.60
Copier	2	0.580	0.50	0.58
Add. Machine	32	0.075	0.35	0.84
Kettle	4	1.500	0.01	0.06
Refrigerator	3	0.250	0.40	0.30
Microwave	2	0.250	0.01	0.01
Drink Fnt.	6	0.250	1.00	1.50
Dish Wash M.	1	0.250	0.38	0.10
Total				6.99

Table A-2.4 Gross steam consumption.

Year	Cumulative Consumption Apr. to Mar. (Ml)	% Increase (+) or Decrease (-)
1976	1.79	
1977	2.09	+17.0
1978	1.23	-41.4
1979	0.83	-32.3
1980	0.93	+11.3
1981	1.79	+93.1
1982	1.67	- 6.8
1983	1.08	-35.2

Table A-2.5 Seven year averages of normalized (January=100.0) monthly steam consumption.

Month	Consumption	Month	Consumption
Jan	100.0	Jul	25.3
Feb	86.8	Aug	22.5
Mar	72.7	Sep	32.4
Apr	55.9	Oct	36.8
May	37.7	Nov	54.2
Jun	25.3	Dec	92.5

APPENDIX A-3: Computer Program Modules for the Initial Load Prediction Model

The following is a computer program listing of the eight modules which were used in the initial prediction model to calculate the total thermal load. Each of these modules has been written in FORTRAN code, with input and output logic derived from Figure 4.12. These modules include:

1. forecasted temperature,
2. solar forecasts,
3. fenestration load,
4. sol-air temperatures,
5. external envelope heat flux,
6. external load,
7. internal load, and
8. infiltration load.

There are a considerable number of comment cards included in the programs. These comment cards, coupled with the discussion in Chapters 3 and 4³, should make the listing self-explanatory.

³See Sections 3.2.3 and 4.2.3.

```

C
C [332,54]FRTEMP.FTN
C
C *****
C *
C * DYNAMIC CONTROL,  MODULE #1 - FORECASTED TEMPERATURE      *
C * -----                                                    *
C * This program computes predicted temperature for 24 hours    *
C * based on outdoor air temperature reading, time and empirical *
C * formulae.                                                    *
C *                                                              *
C *****
C
C DATABASE PH 14-MAR-84
C
C
C PROGRAM FRTEMP
C
C
C   INTEGER*2 EPN(5)      ! OA.T EPN
C   INTEGER*2 IW          ! DB ACCESS ADDRESS
C   INTEGER*2 N           ! INTEGER TIME (HOURS)
C   INTEGER*2 ACCERR      ! PCM ACCESS ERROR CODE
C   INTEGER*2 J           ! INDEX - FORECASTED HOURS
C   REAL*4 OAT            ! OUTDOOR AIR TEMPERATURE
C   REAL*4 TB             ! BASE TEMPERATURE
C   REAL*4 TNI(24)        ! FORECASTED TEMP. VECTOR FOR 24 HRS
C   LOGICAL*1 TIM(8)      ! SYSTEM TIME
C
C UNIT 1 = system defined (subroutine VALEPN)
C UNIT 2 = output file "FRTEMP.OUT"
C UNIT 5 = TI:
C
C
C   * Establish database access
C   -----
C   CALL FMP2DB(IW)
C   IF (IW.EQ. 0) GOTO 1200                                ! DB ACCESS ERROR
C
C   * Get system time
C   -----
C   CALL TIME(TIM)
C
C   * Convert ASCII hours to integer hours
C   -----
C   N=10*(TIM(1)-48)+(TIM(2)-48)
C
C   * Get outdoor air temperature reading for ADM11A005
C   -----
C   EPN(1)='AD'
C   EPN(2)='M1'

```

```

EPN(3)='1A'
EPN(4)='00'
EPN(5)='5'
CALL VALEPN(EPN,2,OAT,IW,ACCERR)
IF (ACCERR .LT. 0) GOTO 1300                                ! PCM ACCESS ERROR
C
C      * Calculate base temperature TB=f(OAT,N)
C      -----
TB=OAT+2*(1.8*COS(0.2618*N)+1.23*SIN(0.2618*N))
1-2*(0.05*COS(0.5236*N)-0.13*SIN(0.5236*N))
C
C      * Compute forecasted temperatures TNI(j)=f(TB,N,j)
C      -----
DO 100 J=1,24
TNI(J)=TB-2*(1.8*COS(0.2618*(N+J))+1.23*SIN(0.2618*
1(N+J)))+2*(0.05*COS(0.5236*(N+J))-0.13*SIN(0.5236*
1(N+J)))
100  CONTINUE
C
C      * Write TNI(j) to FRTEMP.OUT
C      -----
OPEN (UNIT=2, NAME='SY:FRTEMP.OUT', ERR=1100,
1 TYPE='OLD')
CLOSE (UNIT=2, DISPOSE='DELETE')
OPEN (UNIT=2, NAME='SY:FRTEMP.OUT', ERR=1100,
1 FORM='FORMATTED')
DO 200 J=1,24
WRITE(2,150,ERR=1400) TNI(J)
150  FORMAT(1X,F8.3)
200  CONTINUE
CLOSE (UNIT=2, DISPOSE='SAVE')
STOP
C
C      * Error stops
C      -----
1100  CONTINUE
      TYPE 1110
1110  FORMAT(/' FRTEMP--COULD NOT OPEN FRTEMP.OUT !')
      GOTO 1500
1200  CONTINUE
      TYPE 1210
1210  FORMAT(/' FRTEMP--DB ACCESS ERROR !')
      GOTO 1500
1300  CONTINUE
      TYPE 1310
1310  FORMAT(/' FRTEMP--PCM ACCESS ERROR !')
      GOTO 1500
1400  CONTINUE
      TYPE 1410
1410  FORMAT(/' FRTEMP--WRITE ERROR,CHECK FRTEMP.OUT !')
1500  CONTINUE

```



```

C      * Get solar reading from ADM1.S099 (filtered point)
C      -----
EPN(1)='AD'
EPN(2)='M1'
EPN(3)='S'
EPN(4)='09'
EPN(5)='9'
CALL VALEPN(EPN,2,ITH,IW,ACCERR)
IF (ACCERR.LT. 0) GOTO 520      ! PCM ACCESS ERROR

C      * Get system time
C      -----
CALL TIME(TIM)

C      * Convert ACSII hours to integer hours
C      -----
ITIME=10*(TIM(1)-48)+(TIM(2)-48)

C      * Get date
C      -----
CALL IDATE(MONTH,DAY,YEAR)

C      * Compute the number of days from beginning of year
C      -----
NDAY=DAY+30.4*MONTH

C      * Caculate daylight savings indicator DS-
C      -----
Nov thru Apr: DS=0
May thru oct: DS=1

DS=0.
IF ((MONTH.GE.11.).OR.(MONTH.LT.5)) DS=0.
IF ((MONTH.GE.5).AND.(MONTH.LT.11)) DS=1.

C      * Compute apparent solar time AST
C      -----
AST=ITIME-0.5667-DS

C      * Compute angle of declination in radians
C      -----
DELTA=0.4093*SIN(0.017214*(284.+NDAY))

C      * Determine if dark outside by calculating sun rise
C      and sun set times
C      -----
WR=57.2958*ACOS(-1.3383*(TAN(DELTA)))
RISE=12.-(WR/15.)
SET =12.+(WR/15.)
IF ((AST.LE.RISE).OR.(AST.GE.SET)) GOTO 100
IF (ITH.LE.0.0) GOTO 100

```

```

C          * Call SUBE - This subroutine calculates solar
C          intensities using the real-time solar measurement
C
CALL SUBE(NDAY,AST,RISE,SET,DELTA,23,ITH,THETA,SOLAR)
GOTO 200
100    CONTINUE
C
C          * Call SUBF - This subroutine calculates the total
C          solar intensity on each surface without the use
C          of a real-time measurement: used when dark outside.
C
CALL SUBF(NDAY,AST,DELTA,23,ITH,THETA,SOLAR)
200    CONTINUE
C
C          * Delete the old SOLAR.OUT and THETA.OUT
C          -----
OPEN (UNIT=2, NAME='SY:SOLAR.OUT', ERR=540, TYPE='OLD')
CLOSE (UNIT=2, DISPOSE='DELETE')
OPEN (UNIT=3, NAME='SY:THETA.OUT', ERR=580, TYPE='OLD')
CLOSE (UNIT=3, DISPOSE='DELETE')
C
C          * Open new SOLAR.OUT and THETA.OUT
C          -----
OPEN (UNIT=2, NAME='SY:SOLAR.OUT', ERR=540, TYPE='NEW',
1 ACCESS='SEQUENTIAL', FORM='FORMATTED')
OPEN (UNIT=3, NAME='SY:THETA.OUT', ERR=580, TYPE='NEW',
1 ACCESS='SEQUENTIAL', FORM='FORMATTED')
C
C          * Write SOLAR and THETA into the output file
C          -----
DO 300 J=1,24
WRITE (2,250,ERR=560) (SOLAR(J,K),K=1,5)
250    FORMAT(1X,5F10.3)
300    CONTINUE
DO 350 J=1,24
WRITE (3,250,ERR=600) (THETA(J,K),K=1,5)
350    CONTINUE
C
C          * Exit
C          ----
CLOSE (UNIT=2, DISPOSE='SAVE')
CLOSE (UNIT=3, DISPOSE='SAVE')
STOP
C
C          * Error stops
C          -----
500    TYPE 510
510    FORMAT('/ SOLAR -- DATABASE ACCESS ERROR !')
STOP
520    TYPE 530

```

```

530   FORMAT(/' SOLAR -- PCM ACCESS ERROR !')
      STOP
540   TYPE 550
550   FORMAT(/' SOLAR -- COULD NOT OPEN SOLAR.OUT !')
      STOP
560   TYPE 570
570   FORMAT(/' SOLAR -- SOLAR.OUT WRITE ERROR !')
      STOP
580   TYPE 590
590   FORMAT(/' SOLAR -- COULD NOT OPEN THETA.OUT !')
      STOP
600   TYPE 610
610   FORMAT(/' SOLAR -- THETA.OUT WRITE ERROR !')
      STOP
      END

```

```

C
C      #####
C      #          *   SUBROUTINES   *          #
C      #
C      #
C      #####
C
C      #####
C      #
C      SUBROUTINE SUBS(ID,IDN,ITH,DELTA,ALTIT,AST,J
C      1,SOLAR,THETA)
C      #
C      #
C      #      This subroutine determines the total radiation
C      #      incident on given k-th surface.
C      #
C      #####
C
C      * Variables in : ID,IDN,ITH,DELTA,ALTIT,AST,J
C      * Variables out: SOLAR, THETA
C
C      * External variables - see description in the Main Program
C      REAL*4 ID,IDN,ITH,DELTA,ALTIT,AST
C      REAL*4 SOLAR(24,5),THETA(24,5)
C      * Internal variables
C      REAL*4 FACTOR          ! VIEW FACTOR FOR DIRECT RADIATION
C      REAL*4 COEF            ! -//-
C      REAL*4 GAMMA           ! SURFACE - SOLAR AZIMUTH
C      REAL*4 COSPHI          ! COSINE OF SOLAR AZIMUTH
C      REAL*4 FSS             ! VIEW FACTOR - SURFACE TO SKY
C      REAL*4 FSG             ! VIEW FACTOR - SURFACE TO GROUND
C      REAL*4 COSGAM
C      INTEGER*2 J,K          ! COUNTERS
C
C      * Determine view factor
C      -----

```



```

COEF=1.0
IF (AST.GE.12.0) COEF=-1.0

C
C      * Determine type of surface
C      -----
DO 100 K=1,5
  GOTO (10,20,30,40,50) K
C      * For K=1 , north vert. surface
10    FACTOR = 2.0
      GOTO 50
C      * For K=2 , east vert. surface
20    FACTOR = -COEF
      GOTO 50
C      * For K=3 , south vert. surface
30    FACTOR = 0.0
      GOTO 50
C      * For K=5 , a horizontal surface
40    THETA(J,K)=ALTIT
      FSS = 1.0
      FSG = 0.0
      GOTO 55
C      * For K=4, west, factor is not altered
49    FACTOR=COEF
50    COSPHI=(0.8011*ALTIT-SIN(DELTA))/0.5986*COS(ASIN(ALTIT))
      GAMMA=ABS(ACOS(COSPHI)+FACTOR*1.5708)

C
C      * If direct sunlight on surface
C      -----
COSGAM=COS(GAMMA)

C
C      * For surfaces in shade
C      -----
IF (GAMMA.GE.1.5708) COSGAM=0.0

C
C      * Compute THETA (cos phi) for vertical surfaces
C      -----
      THETA(J,K)=COSGAM*COS(ASIN(ALTIT))
      FSS = 0.5
      FSG = 0.5
55    SOLAR(J,K)=1.12*(IDN*THETA(J,K)+FSS*ID+0.2*FSG*ITH)
100   CONTINUE
      RETURN
      END

C
C #####
C # SUBROUTINE SUBR(RATIO,ITH,ID) #
C # #
C # This subroutine determines amount of diffuse radiation #
C # from active data. #
C # #
C #####

```

```

COEF=1.0
IF (AST.GE.12.0) COEF=-1.0

C
C
C      * Determine type of surface
C      -----
DO 100 K=1,5
    GOTO (10,20,30,40,50) K
C      * For K=1 , north vert. surface
10    FACTOR = 2.0
    GOTO 50
C      * For K=2 , east vert. surface
20    FACTOR = -COEF
    GOTO 50
C      * For K=3 , south vert. surface
30    FACTOR = 0.0
    GOTO 50
C      * For K=5 , a horizontal surface
40    THETA(J,K)=ALTIT
    FSS = 1.0
    FSG = 0.0
    GOTO 55
C      * For K=4, west, factor is not altered
49    FACTOR=COEF
50    COSPHI=(0.8011*ALTIT-SIN(DELTA))/0.5986*COS(ASIN(ALTIT)).
    GAMMA=ABS(ACOS(COSPHI)+FACTOR*1.5708)

C
C      * If direct sunlight on surface
C      -----
    COSGAM=COS(GAMMA)

C
C      * For surfaces in shade
C      -----
    IF (GAMMA.GE.1.5708) COSGAM=0.0

C
C      * Compute THETA (cos phi) for vertical surfaces
C      -----
    THETA(J,K)=COSGAM*COS(ASIN(ALTIT))
    FSS = 0.5
    FSG = 0.5
55    SOLAR(J,K)=1.12*(IDN*THETA(J,K)+FSS*ID+0.2*FSG*ITH)
100   CONTINUE
    RETURN
    END

C
C #####
C # SUBROUTINE SUBR(RATIO,ITH,ID) #
C # This subroutine determines amount of diffuse radiation #
C # from active data. #
C # #
C #####

```

```

C
C      Variables in  : RATIO, ITH
C      Variables out : ID
C
REAL*4 ID      ! DIFFUSE RADIATION
REAL*4 ITH     ! TOTAL HORIZONTAL RADIATION
REAL*4 RATIO   ! RATIO OF MEASUREMENT TO CLEAR-SKY TOTAL
C              HORIZONTAL SOLAR RADIATION
IF (RATIO.GE.0.48) GOTO 10
C
C      * For ratio less than 0.48
C      -----
ID = ITH*(1.-0.1*RATIO)
GOTO 50
10  CONTINUE
IF (RATIO.GE.1.10) GOTO 20
C
C      * For 0.48 =< RATIO < 1.10
C      -----
ID = ITH*(1.11-0.396*RATIO-0.789*RATIO*RATIO)
GOTO 50
C
C      * RATIO > 1.10
C      -----
20  ID = 0.20*ITH
50  CONTINUE
RETURN
END
C
C
C
C #####
C # SUBROUTINE SUBI (NDAY,AST,DELTA,IC,ALTIT) #
C # # #
C # This subroutine determines clear-sky total #
C # horizontal radiation with empirical formulae #
C # # #
C #####
C
C      Variables in  : NDAY,AST,DELTA
C      Variables out : IC, ALTIT
C
C      * External variables
REAL*4 NDAY      ! NUMBER OF DAYS FROM BEGINNING OF YEAR
REAL*4 AST       ! APPARENT SOLAR TIME 1-24. HRS
REAL*4 DELTA     ! SOLAR DECLINATION
REAL*4 ALTIT     ! COSINE OF VERTICAL ANGLE OF INCIDENCE
REAL*4 IC        ! TOTAL HORIZ. CLEAR-SKY SOLAR RADIATION
C
C      * Internal variables
REAL*4 TAUB      ! TRANSMISSION COEFFICIENT

```

```
REAL*4 GON      ! EXTRATERRESTRIAL RADIATION
REAL*4 IDHC     ! CLEAR SKY DIRECT HORIZONTAL RADIATION
REAL*4 CLOUD    ! CLOUDINESS FACTOR
```

```
ALTIT = 0.5986*COS(DELTA)*COS((12.-AST)
1*0.2618)+0.8011*SIN(DELTA)
TAUB = 0.1886+0.7007*EXP(-0.3367/ALTIT)
GON = 1353.*(1+0.033*COS(0.017214*NDAY))
IDHC = GON*TAUB*ALTIT
CLOUD = 0.09-0.032*COS(0.01714*(NDAY-30.4))
1+0.012*SIN(0.017214*(NDAY-15.))
IC = IDHC*(1.+CLOUD/ALTIT)
RETURN
END
```

```
#####
#
# SUBROUTINE SUBF(NDAY,AST,DELTA,HOURS,ITH,THETA,SOLAR)
#
#
# Forecasting with no real-time measurements
#
#####
```

```

Variables in      : ITH,NDAY,AST,HOURS
Variables in/out  : DELTA,THETA, SOLAR

```

* External variables

```

REAL*4 NDAY          ! NUMBER OF DAYS FROM BEGINNING OF YEAR
REAL*4 AST           ! APPARENT SOLAR TIME
REAL*4 DELTA         ! SOLAR DECLINATION
REAL*4 THETA(24,5)   ! COSINE OF ANGLE OF INCIDENCE
REAL*4 SOLAR(24,5)   ! TOTAL SOLAR INTENSITIES
INTEGER*2 HOURS       ! NUMBER OF HOURS TO BE FORECASTED

```

* Internal variables

```

REAL*4 COEF1,COEF2,COEF3
REAL*4 ITH          ! TOTAL HORIZONTAL RADIATIN
REAL*4 ID           ! DIFFUSE RADIATION
REAL*4 ALTIT        ! COSINE OF VERTICAL ANGLE OF INCIDENCE
REAL*4 IDN          ! DIRECT NORMAL SOLAR RADIATION
REAL*4 IDH          ! DIRECT HORIZONTAL RADIATION
INTEGER*2 J,K       ! COUNTERS

```

* Compute coefficients used for ITH and ID estimates

```
COEF1 = 190.28*COS(0.017214*(NDAY-182.5))-3.89
COEF2 = 116.39*COS(0.017214*(NDAY-182.5))-10.28
COEF3 = (1.-0.2*SIN(NDAY*0.008607))*(297.22-0.36*N)
```



```

C      * Set up loop for each hour to be forecasted.
C      Calculate ITH and ID. If they are both less
C      than zero, darkness is implied and the next
C      forecasted hour is attempted.
C
C      DO 100 J=1,HOURS+1
C          ITH=COEF1+473.*COS(0.261799*(AST-12.))
C          IF (ITH .LE. 0.0) ITH = 0.0
C          ID = COEF2+COEF3*COS(0.261799*(AST-12.))
C          IF (ID .LE. 0.0) GOTO 50
C
C          * Compute solar altitude sin[BETA]
C          -----
C      ALTIT = 0.5986*COS(DELTA)*COS((12.-AST)*0.2618)+0.8011*SIN(DELTA)
C      IDH = ITH - ID
C      IDN = IDH/ALTIT
C      CALL SUBS(ID,IDN,ITH,DELTA,ALTIT,AST,J,SOLAR,THETA)
C
C      * Increment time one hour
C      -----
C      AST = AST +1.
C      IF (AST.GT.24.0) AST=AST-24.
C      GOTO 90
C
C      * For darkness inference
C      -----
C      CONTINUE
C      DO 70 K=1,5
C          SOLAR(J,K)=0.0
C          THETA(J,K)=0.0
C
C      CONTINUE
C      AST = AST +1.
C      IF (AST.GT.24.0) AST=AST-24.
C      CONTINUE
C      CONTINUE
C
C      RETURN
C      END
C
C      #####
C      SUBROUTINE SUBE(NDAY,AST,RISE,SET,DELTA,HOURS,ITH,THETA,SOLAR)
C      #
C      #      Forecasting with real-time data
C      #
C      #####
C
C      Variables in      :  NDAY,AST,HOURS,ITH
C      Variables in/out :  DELTA,THETA,SOLAR

```

```

C
C
      * External variables
REAL*4 RISE           ! TIME OF SUN RISE 0-12
REAL*4 SET            ! TIME OF SUN SET 12-24
REAL*4 NDAY           ! NUMBER OF DAYS FROM BEGINNING OF YEAR
REAL*4 AST            ! APPARENT SOLAR TIME
REAL*4 DELTA          ! SOLAR DECLINATION
REAL*4 ITH            ! TOTAL HORIZONTAL RADIATION
REAL*4 THETA(24,5)    ! COSINE OF ANGLE OF INCIDENCE
REAL*4 SOLAR(24,5)    ! TOTAL SOLAR INTENSITIES
INTEGER*2 HOURS       ! NUMBER OF HOURS TO BE FORECASTED

C
C
      * Internal variables
REAL*4 IC             ! TOTAL CLEAR-SKY HORIZ. SOLAR RADIATION
REAL*4 ALTIT          ! COSINE OF VERTICAL ANGLE OF INCIDENCE
REAL*4 RATIO          ! RATIO MEASUREMENT/CLEAR-SKY SOLAR RAD.
REAL*4 ID             ! DIFFUSE RADIATION
REAL*4 IDH            ! DIRECT HORIZONTAL RADIATION
REAL*4 IDN            ! DIRECT NORMAL RADIATION
INTEGER*2 J,K         ! COUNTER

C
C
      * Calculate normal clear-sky total horizontal radiation
      -----
      NDAY,AST,DELTA IN ; IC,ALTIT OUT
CALL SUBI(NDAY,AST,DELTA,IC,ALTIT)
      * Compute ratio of actual to clear sky total
      horizontal radiation.
RATIO = ITH/IC

C
C
      * Loop for each hour forecasted
      -----
DO 100 J=1,HOURS+1
  IF ((AST.LE.RISE).OR.(AST.GE.SET)) GOTO 80

  * Subrout. SUBR - RATIO, ITH in ; ID out
  -----
CALL SUBR(RATIO,ITH,ID)
IDH = ITH - ID
IDN = IDH/ALTIT

C
C
  * Subrout. SUBS - ID,IDN,ITH,DELTA,ALTIT,AST,J in
  - SOLAR, THETA out
  -----
CALL SUBS(ID,IDN,ITH,DELTA,ALTIT,AST,J,SOLAR,THETA)
AST = AST + 1.
IF (AST.GT.24.) AST=AST-24.

C
C
  * Compute IC for new hour
  * Subrout. SUBI - NDAY,AST,DELTA in
  - IC, ALTIT out

```

80

0000000000000000000000000000000000

000000

CC

000000

CCC

C

100
120

```

CLOSE (UNIT=2, DISPOSE='SAVE')
C
C      * Read in matrix SOLAR
C      -----
OPEN (UNIT=2, NAME='SY:SOLAR.OUT', ERR=540, TYPE='OLD'
1, READONLY, FORM='FORMATTED')
DO 200 J=1,24
200   READ (2,220,ERR=560,END=560) (SOLAR(J,K),K=1,5)
220   CONTINUE
      FORMAT(1X,5F10.3)
CLOSE (UNIT=2, DISPOSE='SAVE')
C
C      * Read in matrix THETA
C      -----
OPEN (UNIT=2, NAME='SY:THETA.OUT', ERR=580, TYPE='OLD'
1, READONLY, FORM='FORMATTED')
DO 300 J=1,24
300   READ (2,220,ERR=600,END=600) (THETA(J,K),K=1,5)
      CONTINUE
CLOSE (UNIT=2, DISPOSE='SAVE')
C
C      * Compute thermal flux
C      -----
AREA(1)=111.5
AREA(2)=43.9
AREA(3)=138.2
AREA(4)=42.5
DO 450 J=1,24
DO 400 K=1,4
400   THETA(J,K)=ACOS(THETA(J,K))
450   FENEST(J,K)=(0.857+0.205*ALOG(1-0.6296*THETA(J,K)))**2
      FENEST(J,K)=FENEST(J,K)/(1.-((0.106*EXP((0.9549*THETA(J,K))
1**2)-0.08)**2))
      FENEST(J,K)=FENEST(J,K)+0.839*(0.142+0.078*(SIN(THETA(J,K)
1+0.5236))*ALOG(1.667-0.6366*THETA(J,K)))
      FENEST(J,K)=0.5*FENEST(J,K)*SOLAR(J,K)+1.936*(FRTEMP(J)-21.)
      FENEST(J,K)=FENEST(J,K)*AREA(K)*0.001
400   CONTINUE
450   CONTINUE
C      * Delete old FENEST.OUT
C      -----
OPEN (UNIT=3, NAME='SY:FENEST.OUT', ERR=620, TYPE='OLD')
CLOSE (UNIT=3, DISPOSE='DELETE')
C      * Write FENEST to FENEST.OUT
OPEN (UNIT=3, NAME='SY:FENEST.OUT', ERR=620, TYPE='NEW'
1, ACCESS='SEQUENTIAL', FORM='FORMATTED')
DO 480 J=1,24
480   WRITE (3,490,ERR=640) (FENEST(J,K),K=1,4)
490   CONTINUE
      FORMAT(1X,4F10.3)
CLOSE (UNIT=3, DISPOSE='SAVE')
STOP

```



```

C
C
C      * Error stops
C      -----
500    TYPE 510
510    FORMAT(/' FLUX -- COULD NOT OPEN FRTEMP.OUT !')
      STOP
520    TYPE 530
530    FORMAT(/' FLUX -- FRTEMP.OUT READ ERROR !')
      STOP
540    TYPE 550
550    FORMAT(/' FLUX -- COULD NOT OPEN SOLAR.OUT !')
      STOP
560    TYPE 570
570    FORMAT(/' FLUX -- SOLAR.OUT READ ERROR !')
      STOP
580    TYPE 590
590    FORMAT(/' FLUX -- COULD NOT OPEN THETA.OUT !')
      STOP
600    TYPE 610
610    FORMAT(/' FLUX -- THETA.OUT READ ERROR !')
      STOP
620    TYPE 630
630    FORMAT(/' FLUX -- COULD NOT OPEN FENEST.OUT !')
      STOP
640    TYPE 650
650    FORMAT(/' FLUX -- FENEST.OUT WRITE ERROR !')
      CLOSE (UNIT=3, DISPOSE='SAVE')
      STOP
      END

C
C
C
C [332,54]SOTEMP.FTN
C
C
C *****
C * DYNAMIC CONTROL , MODULE #4 : SOL-AIR TEMPERATURE *
C * ----- *
C * *
C * This module calculates predicted outdoor sol-air temperature *
C * for each orientation from predicted outdoor air temperature *
C * (FRTEMP) and from predicted total incident radiation on the given *
C * surface (SOLAR). Vector FRTEMP is read in from the storage *
C * file FRTEMP.OUT and matrix SOLAR is read in from the file *
C * SOLAR.OUT. The calculated sol-air vector is written in the output *
C * file SOTEMP.OUT. *
C * *
C *****
C
PROGRAM SOTEMP

```

```

C
C
REAL*4 FRTEMP(24)          ! FORECASTED TEMPERATURE
REAL*4 SOLAR(24,5)         ! FORECASTED SOLAR IRRADIATION
REAL*4 SOTEMP(24,5)        ! FORECASTED SOL-AIR TEMPERATURE
INTEGER*2 J,K

C
C
OPEN (UNIT=2, NAME='SY:FRTEMP.OUT', ERR=500
1, FORM='FORMATTED', TYPE='OLD', READONLY)

C
C
DO 80 J=1,24
C
50   FORMAT(1X,F8.3)
80   CONTINUE
CLOSE (UNIT=2, DISPOSE='SAVE')

C
C
      * Read in SOLAR matrix
      -----
OPEN (UNIT=2, NAME='SY:SOLAR.OUT', ERR=540
1, FORM='FORMATTED', TYPE='OLD', READONLY)
DO 150 J=1,24
100  READ(2,100,END=560,ERR=560) (SOLAR(J,K),K=1,5)
150  FORMAT(1X,5F10.3)
      CONTINUE
CLOSE (UNIT=2, DISPOSE='SAVE')

C
C
      * Calculate solair temperature
      -----
DO 200 J=1,24
DO 180 K=1,5
SOTEMP(J,K)=FRTEMP(J)+0.038*SOLAR(J,K)

C
C
      * If surface is horizontal, add a correction factor
      -----
IF (K.EQ.5) SOTEMP(J,K)=SOTEMP(J,K)-3.9
180  CONTINUE
200  CONTINUE

C
C
      * Delete old SOTEMP.OUT
      -----
OPEN (UNIT=2, NAME='SY:SOTEMP.OUT', ERR=580,
1 TYPE='OLD')
CLOSE (UNIT=2, DISPOSE='DELETE')

C
C
      * Create a new output file
      -----
OPEN (UNIT=2, NAME='SY:SOTEMP.OUT', ERR=580,
1 TYPE='NEW', FORM='FORMATTED')
DO 250 J=1,24
WRITE (2,100,ERR=600) (SOTEMP(J,K),K=1,5)

```

```

250     CONTINUE
      CLOSE (UNIT=2, DISPOSE='SAVE')
      STOP

C
C           * Error stops
C           -----
500     TYPE 510
510     FORMAT(/' SOTEMP -- FRTEMP.OUT OPEN ERROR !')
      STOP
520     TYPE 530
530     FORMAT(/' SOTEMP -- FRTEMP.OUT READ ERROR !')
      STOP
540     TYPE 550
550     FORMAT(/' SOTEMP -- SOLAR.OUT OPEN ERROR !')
      STOP
560     TYPE 570
570     FORMAT(/' SOTEMP -- SOLAR.OUT READ ERROR !')
      STOP
580     TYPE 590
590     FORMAT(/' SOTEMP -- SOTEMP.OUT OPEN ERROR !')
      STOP
600     TYPE 610
610     FORMAT(/' SOTEMP -- SOTEMP.OUT WRITE ERROR !')
      CLOSE (UNIT=2, DISPOSE='SAVE')
      STOP
      END

C
C [332,54]CONDUCT.FTN
C
C *****
C *
C * DYNAMIC CONTROL , MODULE #5 :  EXTERNAL ENVELOPE HEAT FLUX
C * -----
C *
C * This module calculates the predicted total heat conduction
C * through opaque external walls and roof to the interior.
C * Sol-air temperature is read in from SOTEMP.OUT.  Values of
C * TEFFW, TEFFR, QWALL, QROOF will be retrieved and stored in
C * the following manner:
C *
C * - TEFFW(1) thru TEFFW(6) retrieved from TEFFW.STR file; bottom
C *   value in the file ,TEFFW(6), is the most recent value stored an
C *   hour ago.  TEFFW(1) is a value 6 hours old.
C *
C * - TEFFW(7) thru TEFFW(30) are the new calculated values, TEFFW(7)
C *   is the present value.
C *
C * - TEFFW(2) thru TEFFW(7) will be stored
C *
C * The same applies for  TEFFR, QWALL, QROOF.
C *
C *****

```

C
C
C
C
C
C
C

PROGRAM CONDOC

REAL*4 RTEMP	! ROOM TEMPERATURE
REAL*4 SOTEMP(24,5)	! PREDICTED SOL-AIR TEMPERATURE
REAL*4 TEFFW(30)	! EFFECTIVE WALL SOL-AIR TEMP
REAL*4 TEFFR(30)	! EFFECTIVE ROOF SOL-AIR TEMP
REAL*4 QWALL(30)	! HEAT FLUX THRU INSIDE WALLS
REAL*4 QROOF(30)	! HEAT FLUX THRU ROOF
REAL*4 CONDOC(24)	! TOTAL HEAT CONDUCTION
INTEGER*2 IW	! DATABASE ADDRESS
INTEGER*2 ACCERR	! PCM ACCESS ERROR
INTEGER*2 EPN(5)	! ROOM TEMPERATURE EPN
INTEGER*2 J,K	

C
C UNIT 1 = used by access subroutines
C UNIT 5 = TI:
C
C
C

* Initialize vectors

DO 10 J=1,30
TEFFW(J)=0
TEFFR(J)=0
QWALL(J)=0
QROOF(J)=0
CONTINUE

10
C
C
C

* Establish database access

CALL FMP2DB(IW)
IF (IW .EQ. 0) GOTO 500

C
C
C

* Get average space temperature ADM1.S003

EPN(1)='AD'
EPN(2)='M1'
EPN(3)='S'
EPN(4)='00'
EPN(5)='3'
CALL VALEPN(EPN,2,RTEMP,IW,ACCERR)
IF (ACCERR .LT. 0) GOTO 520

C
C
C

* Read in sol-air temperature

OPEN (UNIT=2, NAME='SY:SOTEMP.OUT', ERR=540,
1 TYPE='OLD', FORM='FORMATTED', READONLY)
DO 25 J=1,24
READ (2,20,END=540,ERR=540) (SOTEMP(J,K),K=1,5)


```

20      FORMAT(1X,5F10.3)
25      CONTINUE
      CLOSE (UNIT=2, DISPOSE='SAVE')

C
C      * Read in storage values XXXXX(1) thru XXXXX(6)
C      for TEFFW, TEFFR, QWALL, QROOF
C
      OPEN (UNIT=2, NAME='SY:CONDUCT.STR', ERR=580,
1 TYPE='OLD', FORM='FORMATTED', READONLY)
      DO 80 J=1,6
      READ(2,30,ERR=600,END=600) TEFFW(J),TEFFR(J),QWALL(J)
1,QROOF(J)
30      FORMAT(1X,4F10.3)
80      CONTINUE
      CLOSE (UNIT=2, DISPOSE='SAVE')

C
C      * Calculate effective sol-air temps. for walls and roof
C
      DO 200 J=1,24
      TEFFW(J+6)=0.346*SOTEMP(J,1)+0.154*SOTEMP(J,2)
1+0.297*SOTEMP(J,3)+0.202*SOTEMP(J,4)
      TEFFR(J+6)=SOTEMP(J,5)
200     CONTINUE

C
C      * Calculate heat flux and total heat gain
C
      DO 250 J=1,24
      QWALL(J+6)=0.0017*TEFFW(J+4)+0.0045*TEFFW(J+3)
1      +0.0028*TEFFW(J+2)+0.0006*TEFFW(J+1)
1      +2.2886*QWALL(J+5)-1.8666*QWALL(J+4)
1      +0.6650*QWALL(J+3)-0.1043*QWALL(J+2)
1      +0.0061*QWALL(J+1)-0.0001*QWALL(J)
1      -0.0091*RTEMP
      QROOF(J+6)=0.0023*TEFFR(J+5)+0.0091*TEFFR(J+4)
1      +0.0040*TEFFR(J+3)+1.4117*QROOF(J+5)
1      -0.4844*QROOF(J+4)+0.0513*QROOF(J+3)
1      -0.0006*QROOF(J+2)-0.0153*RTEMP
      CONDUCT(J)=0.001*(2104.6*QWALL(J+6)+1187.3*QROOF(J+6))
250     CONTINUE

C
C      * Delete old CONDUCT.OUT
C
      OPEN (UNIT=2, NAME='SY:CONDUCT.OUT', ERR=620, TYPE='OLD')
      CLOSE (UNIT=2, DISPOSE='DELETE')

C
C      * Create a new CONDUCT.OUT
C
      OPEN (UNIT=2, NAME='SY:CONDUCT.OUT', ERR=620,
1 TYPE='NEW', FORM='FORMATTED')
      DO 280 J=1,24
      WRITE (2,270,ERR=640) CONDUCT(J)
270     FORMAT(1X,F8.3)

```

```

280      CONTINUE
      CLOSE (UNIT=2, DISPOSE='SAVE')
C
C      * Store XXXXX(2) thru XXXXX(7) for TEFFW, TEFFR,
C      QWALL, QROOF
C      -----
      OPEN (UNIT=2, NAME='SY:CONDUCT.STR', ERR=580, TYPE='OLD')
      CLOSE (UNIT=2, DISPOSE='DELETE')
      OPEN (UNIT=2, NAME='SY:CONDUCT.STR', ERR=580,
      1 TYPE='NEW', FORM='FORMATTED')
      DO 300 J=2,7
      WRITE (2,30,ERR=680) TEFFW(J),TEFFR(J),QWALL(J)
      1,QROOF(J)
300      CONTINUE
      CLOSE (UNIT=2, DISPOSE='SAVE')
      STOP
C
C
C      * Error stops
C      -----
500      TYPE 510
510      FORMAT(/' CONDUCT -- DATABASE ACCESS ERROR !')
      STOP
520      TYPE 530
530      FORMAT(/' CONDUCT -- PCM ACCESS ERROR !')
      STOP
540      TYPE 550
550      FORMAT(/' CONDUCT -- SOTEMP.OUT OPEN OR READ ERROR !')
      STOP
580      TYPE 590
590      FORMAT(/' CONDUCT -- STORAGE OPEN ERROR !')
      STOP
600      TYPE 610
610      FORMAT(/' CONDUCT -- STORAGE READ ERROR !')
      STOP
620      TYPE 630
630      FORMAT(/' CONDUCT -- CONDUCT.OUT OPEN ERROR !')
      STOP
640      TYPE 650
650      FORMAT(/' CONDUCT -- CONDUCT.OUT WRITE ERROR !')
      STOP
680      TYPE 690
690      FORMAT(/' CONDUCT -- STORAGE WRITE ERROR !')
      STOP
      END
C
C [332,54]EXTLOD.FTN
C

```



```

C      * Retrieve EXTERN(1) and EXTLD(1), one hour old values,
C      from storage
C      -----
OPEN (UNIT=2, NAME='SY:EXTLOD.STR', ERR=540,
1 TYPE='OLD', FORM='FORMATTED', READONLY)
READ (2,80,ERR=540) EXTERN(1)
READ (2,80,ERR=540) EXTLD(1)
CLOSE (UNIT=2, DISPOSE='SAVE')

C      * Calculate total window gain and total external load
C      -----
DO 150 J=1,24
WINDOW(J)=FENEST(J,1)+FENEST(J,2)+FENEST(J,3)+FENEST(J,4)
EXTERN(J+1)=CONDOC(J)+WINDOW(J)
150  CONTINUE

C      * Calculate total external conduction load
C      -----
DO 200 J=2,25
EXTLD(J)=0.541*EXTERN(J)-0.509*EXTERN(J-1)+0.96*EXTLD(J-1)
200  CONTINUE

C      * Delete old EXTLOD.OUT
C      -----
OPEN (UNIT=2, NAME='SY:EXTLOD.OUT', ERR=560, TYPE='OLD')
CLOSE (UNIT=2, DISPOSE='DELETE')

C      * Create a new output file
C      -----
OPEN (UNIT=2, NAME='SY:EXTLOD.OUT', ERR=560, TYPE='NEW',
1 FORM='FORMATTED')
DO 250 J=2,25
WRITE (2,80,ERR=560) EXTLD(J)
250  CONTINUE
CLOSE (UNIT=2, DISPOSE='SAVE')

C      * Delete old storage file
C      -----
OPEN (UNIT=2, NAME='SY:EXTLOD.STR', ERR=600, TYPE='OLD')
CLOSE (UNIT=2, DISPOSE='DELETE')

C      * Store present EXTERN and EXTLD
C      -----
OPEN (UNIT=2, NAME='SY:EXTLOD.STR', ERR=600, TYPE='NEW',
1 FORM='FORMATTED')
WRITE (2,80,ERR=600) EXTERN(2)
WRITE (2,80,ERR=600) EXTLD(2)
CLOSE (UNIT=2, DISPOSE='SAVE')
STOP

C
C
C

```



```

C          * Error stops
C          -----
500      TYPE 510
510      FORMAT(/' EXTLOD -- FENEST.OUT OPEN OR READ ERROR !')
        STOP
520      TYPE 530
530      FORMAT(/' EXTLOD -- CONDOC.OUT OPEN OR READ ERROR !')
        STOP
540      TYPE 550
550      FORMAT(/' EXTLOD -- EXTLOD.STR OPEN OR READ ERROR !')
        STOP
560      TYPE 570
570      FORMAT(/' EXTLOD -- EXTLOD.OUT OPEN OR WRITE ERROR !')
        CLOSE (UNIT=2, DISPOSE='SAVE')
        STOP
600      TYPE 610
610      FORMAT(/' EXTLOD -- EXTLOD.STR OPEN OR WRITE ERROR !')
        CLOSE (UNIT=2, DISPOSE='SAVE')
        STOP
        END

C
C
C
C [332,54] INTLOD.FTN
C
C
C
C *****
C *
C * DYNAMIC CONTROL , MODULE #7 : INTERNAL LOAD
C * -----
C *
C * This module creates total internal cooling load vector for
C * next 24 hours. The vector is stored in INTLOD.OUT.
C *
C *****
C
C      PROGRAM INTLOD
C
C
C      REAL*4 INTLOD(24)          ! TOTAL INTERNAL COOLING LOAD
C      INTEGER*2 ITIM              ! INTEGER HOURS
C      INTEGER*2 J
C      LOGICAL*1 TIM(8)           ! ACSII TIME
C
C          * Get system time
C          -----
C      CALL TIME(TIM)
C
C          * Convert ACSII hours to integer hours
C          -----
C      ITIM=10*(TIM(1)-48)+(TIM(2)-48)

```

```

DO 100 J=1,24
IF (ITIM.EQ.0) INTLOD(J)=161.7
IF (ITIM.EQ.1) INTLOD(J)=126.2
IF (ITIM.EQ.2) INTLOD(J)=124.5
IF (ITIM.EQ.3) INTLOD(J)=105.1
IF (ITIM.EQ.4) INTLOD(J)=143.4
IF (ITIM.EQ.5) INTLOD(J)=148.0
IF (ITIM.EQ.6) INTLOD(J)=179.6
IF (ITIM.EQ.7) INTLOD(J)=190.3
IF (ITIM.EQ.8) INTLOD(J)=274.3
IF (ITIM.EQ.9) INTLOD(J)=291.7
IF (ITIM.EQ.10) INTLOD(J)=327.7
IF (ITIM.EQ.11) INTLOD(J)=334.9
IF (ITIM.EQ.12) INTLOD(J)=330.6
IF (ITIM.EQ.13) INTLOD(J)=309.1
IF (ITIM.EQ.14) INTLOD(J)=320.1
IF (ITIM.EQ.15) INTLOD(J)=321.7
IF (ITIM.EQ.16) INTLOD(J)=323.2
IF (ITIM.EQ.17) INTLOD(J)=292.1
IF (ITIM.EQ.18) INTLOD(J)=255.0
IF (ITIM.EQ.19) INTLOD(J)=252.7
IF (ITIM.EQ.20) INTLOD(J)=222.2
IF (ITIM.EQ.21) INTLOD(J)=191.8
IF (ITIM.EQ.22) INTLOD(J)=170.2
IF (ITIM.EQ.23) INTLOD(J)=148.0
ITIM=ITIM+1
IF (ITIM.GT.23) ITIM=ITIM-24
CONTINUE

100 C
C      * Delete old INTLOD.OUT
C      -----
OPEN (UNIT=2, NAME='SY:INTLOD.OUT', ERR=200, TYPE='OLD')
CLOSE (UNIT=2, DISPOSE='DELETE')

C
C      * Create a new file
C      -----
OPEN (UNIT=2, NAME='SY:INTLOD.OUT', ERR=200, TYPE='NEW',
1 FORM='FORMATTED')
DO 150 J=1,24
WRITE (2,130,ERR=220) INTLOD(J)
130   FORMAT(1X,F8.3)
150   CONTINUE
CLOSE (UNIT=2, DISPOSE='SAVE')
STOP

C
C
C      * Error stops
C      -----
200   TYPE 210
210   FORMAT(/' INTLOD -- INTLOD.OUT OPEN ERROR !')
STOP
220   TYPE 230

```

```

230  FORMAT(/' INTLOD -- INTLOD.OUT WRITE ERROR !')
      CLOSE (UNIT=2, DISPOSE='SAVE')
      STOP
      END

```

```

C
C
C
C
C [332,54] INFLOD.FTN
C
C *****
C *
C * DYNAMIC CONTROL MODULE #8 - INFILTRATION LOAD
C * -----
C *
C * This module reads in the forecasted temperature vector from
C * FRTEMP.OUT (module FRTEMP.FTN) and computes the total
C * cooling load due to infiltration. The output values of
C * LEAKLOAD(24) are written into the output file INFLOD.OUT.
C *
C *****
C
C
C PROGRAM INFLOD
C
C
C REAL*4 TEMP(24)      ! FORECASTED TEMPERATURE (DEG. C)
C REAL*4 PRESS(24)     ! DIFF. PRESS. ACROSS BUILDING
C REAL*4 FLOW(24)       ! INFILTRATION RATE
C REAL*4 LEAKLD(24)    ! TOTAL COOLING/HEATING INFILTRATION LOAD
C INTEGER*2 ITIM       ! INTEGER TIME (HOURS)
C INTEGER*2 J          ! INDEX
C LOGICAL*1 TIM(8)     ! ASCII TIME
C
C
C      * Set up error returns
C
C      CALL ERRSET(24,.TRUE.,.FALSE.,.TRUE.,.FALSE.)  IEOF
C      CALL ERRSET(29,.TRUE.,.FALSE.,.TRUE.,.FALSE.)  INSF
C
C
C UNIT 2 = FRTEMP.OUT - Predicted temperatures for 24 hrs
C UNIT 4 = INFLOD.OUT - LEAKLD(J) output file
C UNIT 5 = TI:
C
C      OPEN (UNIT=2, NAME='SY:FRTEMP.OUT',ERR=800,
C            1 FORM='FORMATTED', TYPE='OLD', READONLY)
C
C
C      * Read in the forecasted temperature vector
C      -----
C
C      DO 180 J=1,24
C      READ(2,110,END=190,ERR=820) TEMP(J)

```

```

110  FORMAT(1X,F8.3)
180  CONTINUE
C
C      * Check if all 24 readings were read in
C      -----
190  CONTINUE
    IF (J.LT.24) GOTO 820          ! LINES MISSING IN FRTEMP.OUT
C
C      * Get system time
C      -----
    CALL TIME(TIM)
C
C      * Convert ASCII hours to integer hours
C      -----
    ITIM=10*(TIM(1)-48)+(TIM(2)-48)
C
C      * Calculate the theoretical pressure across building
C      and the flow rate induced
C      -----
    DO 600 J=1,24
      PRESS(J)=(5.+0.246*(ABS(20.-TEMP(I))))/249.1
      FLOW(J)=0.472*(330.*PRESS(J)**0.66+11767.*PRESS(J)
      1**0.5+92.*PRESS(J)**0.8)
C
C      * Modify flow rate according to occupancy profile
C      -----
    IF (((ITIM.NE.7).AND.(ITIM.NE.8).AND.(ITIM.NE.12)
    1.AND.(ITIM.NE.13).AND.(ITIM.NE.16).AND.
    1(ITIM.NE.17)) GOTO 400
C
C      * For higher traffic periods
    FLOW(J)=2.*FLOW(J)
C
C      * For lower traffic periods
400  CONTINUE
    IF (((ITIM.GT.8).AND.(ITIM.LT.12)).OR.(((ITIM.GT.13)
    1.AND.(ITIM.LT.16))) FLOW(J)=1.2*FLOW(J)
C
C      * For all other periods (evenings)
C      flow value unaltered.
500  CONTINUE
C
C      * Calculate estimated cooling load due to air
C      infiltration (KW)
C      -----
    LEAKLD(J)=0.0016*FLOW(J)*(TEMP(J)-21.)
C
C      * Increase time integer value by one hour
    IF (ITIM.EQ.23) ITIM=-1
    ITIM=ITIM+1
600  CONTINUE

```



```

C
C      * Write LEAKLD(J) to the output file INFLOD.OUT
C      -----
      OPEN (UNIT=4, NAME='SY:INFLOD.OUT', ERR=840,
1 FORM='FORMATTED', TYPE='OLD')
      CLOSE (UNIT=4, DISPOSE='DELETE')
      OPEN (UNIT=4, NAME='SY:INFLOD.OUT', ERR=840,
1 FORM='FORMATTED', TYPE='NEW', DISPOSE='SAVE')
      DO 750 J=1,24
      WRITE (4,110,ERR=860) LEAKLD(J)
750    CONTINUE
      GOTO 1000

C
C      * Error stops
C      -----
800    CONTINUE
      TYPE 810
810    FORMAT(/' INFLOD -- FRTEMP.OUT MISSING !'/)
      GOTO 1000
820    CONTINUE
      TYPE 830
830    FORMAT(/' INFLOD -- FRTEMP.OUT READ ERROR !'/)
      GOTO 1000
840    CONTINUE
      TYPE 850
850    FORMAT(/' INFLOD -- INFLOD.OUT OPEN ERROR !'/)
      GOTO 1000
860    CONTINUE
      TYPE 870
870    FORMAT(/' INFLOD -- INFLOD.OUT WRITE ERROR !'/)
C      * EXIT
1000   CONTINUE
      STOP
      END

```

APPENDIX A-4: Computer Program for the Pilot Control System

The following is a computer program listing which was run on the University of Alberta RCMS host. Coded in FORTRAN, this listing is presented in the following sections:

1. Initialization. Real-time measurements from the PCM and values retrieved from storage are read.
2. Supply air differential pressure set point. The empirical value for S007 is calculated, and sent to the PCM for hot-deck control during normal operation and warmup cycle.
3. Precooling initiation. The optimum duration of precooling before occupancy is computed. Switches SY01 and PC01 are turned on when the precooling duration calculated equals the time left before 7:30 (real time).
4. Precooling termination. Run at 7:30 (real time), this section turns off precooling switch PC01 and updates the mass temperature rate vector storage.
5. Subroutines. Holidays and weekdays are calculated in conjunction with the University of Alberta optimization software.

A large number of comment cards are included within the listing to supplement the description above.

[332,54] DYNCON.FTN

```

*****
*
* OPTIMUM STARTUP AND DYNAMIC CONTROL PROGRAM:
* -----
*
* The program calculates predicted loads, determines the time of
* optimum startup, calculates cooling load during the economized
* mode, communicates with the PCM, initiates the optimum startup
* and fresh air cooling during economized mode.
*
* STORAGE: 'DCEXEC.STR' stores 'MASSP' - core temperature at the
* optimum startup time. TIMV.STR stores self- adaptive constants
* determining correction for the next startup time.
*
* This program should be run a rescheduled task every hour at
* hour:30 to hour:45 .
*
*****

```

Language : FORTRAN IV

Subroutines : FMP2DB,VALEPN,PUTEPN (Access library)
HOLDAY,WKDAY

PH 20-JUNE-84

PROGRAM DYNCON

REAL*4 TIMV(5)	! SELF-ADAPTIVE CORRECTION CONSTANTS
REAL*4 PC01	! PRECOOLING SWITCH STATUS
REAL*4 OAT	! OUTDOOR AIR TEMPERATURE
REAL*4 MASSD	! DESIRED MASS TEMPERATURE
REAL*4 MASSP	! PRESENT MASS TEMPERATURE
REAL*4 MASS7	! MASS TEMPERATURE AT 7 A.M.
REAL*4 STFAN	! FAN STARTUP TIME
REAL*4 RINIT	! REAL STARTUP TIME
REAL*4 VALUE	! GENERAL VARIABLE
REAL*4 TB	! BASE TEMPERATURE
REAL*4 TMAX	! MAXIMUM TEMPERATURE
REAL*4 ECO1	! ECONO SWITCH STATUS
REAL*4 TBLDG	! BUILDING TEMPERATURE
REAL*4 SOLAR	! SOLAR READING
REAL*4 ECOCAP	! ECONO CAPACITY
REAL*4 INTLOD	! INTERNAL LOAD
REAL*4 TOTLOD	! TOTAL LOAD
REAL*4 HTLOAD	! HEAT LOAD

```

REAL*4 S007          ! ADM1.S007 VALUE
REAL*4 SY01          ! SYSTEM SWITCH STATUS
LOGICAL*1 TIM(8)      ! SYSTEM TIME
LOGICAL*1 DAT(9)      ! SYSTEM DATE
INTEGER*2 ITIM        ! INTEGER TIME (HOURS)
INTEGER*2 IW          ! DATABASE ACCESS ADDRESS
INTEGER*2 EPN(5)      ! EXTERNAL POINT NUMBER NAME
INTEGER*2 ACCERR      ! PCM ACCESS ERROR
INTEGER*2 INIT        ! INTEGER STARTUP TIME
INTEGER*2 TODAY       ! HOLIDAY INDICATOR FOR TODAY
INTEGER*2 TOMRW       ! HOLIDAY INDICATOR FOR TOMMORROW
INTEGER*2 J,K         ! INDEXES,COUNTERS

```

C
C UNIT 1 = Used by access subroutines

C UNIT 2 = Input and storage files

C ***** INITIALIZATION AND GENERAL *****

C
C
C
C
C
C
C * Retrieve TIMV from TIMV.STR , FORMAT 1X,4F12.4

OPEN (UNIT=2, NAME='SY:TIMV.STR', FORM='FORMATTED',
1 READONLY, TYPE='OLD')

READ (2,5) (TIMV(J),J=1,4)

5 FORMAT(1X,4F12.4)

C CLOSE (UNIT=2, DISPOSE='SAVE')

C
C * Get current system time

C
C CALL TIME(TIM)

C
C * Convert ACSII hours to integer hours

C
C ITIM=10*(TIM(1)-48)+(TIM(2)-48)

C
C * Establish database access

C CALL FMP2DB(IW)

C IF (IW .EQ. 0) GOTO 500

! DATABASE ACCESS ERROR

C
C * Get system switch ADM1.SY01 status

C EPN(1)='AD'

C EPN(2)='M1'

C EPN(3)='S'

C EPN(4)='YO'

C EPN(5)='1'

C CALL VALEPN(EPN,2,SY01,IW,ACCERR)

C IF (ACCERR .LT. 0) GOTO 520

! PCM ACCESS ERROR

C
C * Get precooling switch status ADM1.PC01


```

EPN(1)='AD'
EPN(2)='M1'
EPN(3)='P'
EPN(4)='CO'
EPN(5)='1'
CALL VALEPN(EPN,2,PC01,IW,ACCERR)
IF (ACCERR .LT. 0) GOTO 520                ! PCM ACCESS ERROR

```

```

* Get outdoor air temperature reading for ADM11A005
-----

```

```

EPN(1)='AD'
EPN(2)='M1'
EPN(3)='1A'
EPN(4)='00'
EPN(5)='5'
CALL VALEPN(EPN,2,OAT,IW,ACCERR)
IF (ACCERR .LT. 0) GOTO 520                ! PCM ACCESS ERROR

```

```

* Get the current value for ADM1.EC01
-----

```

```

EPN(1)='AD'
EPN(2)='M1'
EPN(3)='E'
EPN(4)='CO'
EPN(5)='1'
CALL VALEPN(EPN,2,EC01,IW,ACCERR)
IF (ACCERR .LT. 0) GOTO 520                ! PCM ACCESS ERROR

```

```

* Call HOLIDAY and WEEKDAY subroutine
-----

```

```

CALL HOLDAY(TODAY,TOMRW)

```

```

***** SUPPLY AIR DIFFERENTIAL PRESSURE SETPOINT*****
-----

```

This routine calculates predicted cooling (resp. heating) requirement during normal operating mode and sends a number from 21C to 25C to ADM1.S007. In the PCM this number is transformed into a SA.DP setpoint.

```

* If today is NOT a weekend skip this routine
-----

```

```

IF (TODAY.EQ.1) GOTO 200

```

```

* Run the routine if 7 < ITIM < 16 (7:30-15:30)
-----

```

```

IF ((ITIM.LT.7).OR.(ITIM.GT.16)) GOTO 200

```

C
C* Get the current value for bld.t ADM1.S006

EPN(1)='AD'

EPN(2)='M1'

EPN(3)='S'

EPN(4)='00'

EPN(5)='6'

CALL VALEPN(EPN,2,TBLDG,IW,ACCERR)

IF (ACCERR .LT. 0) GOTO 520

! PCM ACCESS ERROR

C
C
C* Get the solar reading ADM1.S099

EPN(1)='AD'

EPN(2)='M1'

EPN(3)='S'

EPN(4)='09'

EPN(5)='9'

CALL VALEPN(EPN,2,SOLAR,IW,ACCERR)

IF (ACCERR .LT. 0) GOTO 520

! PCM ACCESS ERROR

C
C
C* Internal load

IF (ITIM .EQ. 0) INTLOD = 161.7

IF (ITIM .EQ. 1) INTLOD = 126.2

IF (ITIM .EQ. 2) INTLOD = 124.5

IF (ITIM .EQ. 3) INTLOD = 105.1

IF (ITIM .EQ. 4) INTLOD = 143.4

IF (ITIM .EQ. 5) INTLOD = 148.0

IF (ITIM .EQ. 6) INTLOD = 179.6

IF (ITIM .EQ. 7) INTLOD = 190.3

IF (ITIM .EQ. 8) INTLOD = 274.6

IF (ITIM .EQ. 9) INTLOD = 291.7

IF (ITIM .EQ. 10) INTLOD = 327.7

IF (ITIM .EQ. 11) INTLOD = 334.9

IF (ITIM .EQ. 12) INTLOD = 330.6

IF (ITIM .EQ. 13) INTLOD = 309.1

IF (ITIM .EQ. 14) INTLOD = 320.1

IF (ITIM .EQ. 15) INTLOD = 321.7

IF (ITIM .EQ. 16) INTLOD = 323.2

IF (ITIM .EQ. 17) INTLOD = 292.1

IF (ITIM .EQ. 18) INTLOD = 255.0

IF (ITIM .EQ. 19) INTLOD = 252.7

IF (ITIM .EQ. 20) INTLOD = 222.2

IF (ITIM .EQ. 21) INTLOD = 191.8

IF (ITIM .EQ. 22) INTLOD = 170.2

IF (ITIM .EQ. 23) INTLOD = 148.0

C
C
C
C
C* Calculate total load

TOTLOD = INTLOD-70.0+70.0*(SOLAR/1000.0)

```

C          * Calculate econo capacity
C          -----
C          ECOCAP = 21.58*(23.0-OAT)
C          IF (ECOCAP.LE.100.0) ECOCAP=0.0
C
C          * Calculate heat load
C          -----
C          HTLOAD = TOTLOD - ECOCAP
C
C          * Calculate .S007 value
C          -----
C          S007 = TBLDG + (0.005*HTLOAD)
C
C          * Limit the calculated value between 15 and 40 C
C          -----
C
C          IF (S007 .LT. 15.0) S007=15.0
C          IF (S007 .GT. 40.0) S007=40.0
C
C          *****
C          The following conditionals prevent the building
C          air system from providing excessive warmup
C          periods during the warmer weather.
C          *****
C
C          * 7:00 warmup SA.DP setpoint adjustment
C          -----
C          IF (ITIM .NE. 7) GOTO 100
C          IF (OAT .GE. 12.0) GOTO 99
C          IF (OAT .GE. 6.0) GOTO 98
C          IF (OAT .LT. 0.0) GOTO 109
C
C          * For OAT between 0 and 6C
C          IF ((TBLDG.LT.22.3).AND.(S007.LE.23.0)) S007=23.0
C          IF (TBLDG.GE.22.3) S007=25.0
C          GOTO 109
C
C          * For OAT between 6 and 12C
C          98 CONTINUE
C          IF ((TBLDG.LT.22.0).AND.(S007.LE.23.5)) S007=23.5
C          IF (TBLDG.GE.22.0) S007=25.0
C          GOTO 109
C
C          * For OAT >= 12C
C          99 CONTINUE
C          IF ((TBLDG.LT.21.0).AND.(S007.LE.24.0)) S007=24.0
C          IF (TBLDG.GE.21.0) S007=25.0
C          GOTO 109
C          100 CONTINUE
C
C          * 8:00 warmup SA.DP setpoint adjustment
C          -----

```

```

IF (ITIM .NE. 8) GOTO 109
IF (OAT .GE. 12.0) GOTO 108
IF (OAT .GE. 6.0) GOTO 107
IF (OAT .LT. 0.0) GOTO 109
C      * For OAT between 0 and 6C
IF ((TBLDG.LT.22.6).AND.(S007.LE.23.0)) S007=23.0
IF (TBLDG .GE. 22.6) S007=25.0
GOTO 109

```

```

C      * For OAT between 6 and 12C
107 CONTINUE
IF ((TBLDG.LT.22.3).AND.(S007.LE.23.5)) S007=23.5
IF (TBLDG.GE.22.3) S007=25.0
GOTO 109

```

```

C      * For OAT >= 12C
108 CONTINUE
IF ((TBLDG.LT.21.8).AND.(S007.LE.24.0)) S007=24.0
IF (TBLDG.GE.21.8) S007=25.0
109 CONTINUE

```

```

C      * Send S007 value to PCM
C      -----
C

```

```

EPN(1)='AD'
EPN(2)='M1'
EPN(3)='.S'
EPN(4)='00'
EPN(5)='7'
CALL PUTEPN(EPN,2,S007,IW,ACCERR)
IF (ACCERR .LT. 0) GOTO 520          ! PCM ACCESS ERROR
200 CONTINUE

```

*****OPTIMUM STARTUP*****

Since precooling can be initiated only during preoccupancy hours, this routine will run from 17:00 to 6:00 (INCL). When the precooling switch is in this routine will be skipped.

During weekends and holidays the routine will be disabled. This includes Friday 17:00 thru 24:00 and the same time for the day before a holiday. Routine will be enabled on Sunday night (for Monday precooling) unless Monday is a holiday.

The precooling switch will be turned off at 7:00.

```

IF (PC01.EQ.1.0) GOTO 300          ! SKIP
IF ((ITIM.LT.17).AND.(ITIM.GT.6)) GOTO 300    ! SKIP

```

* Routine enable/disable conditionals:

Today	Tomrw	Time	Condition	Comment
0	0	N/A	Enable	
1	0	0-6 A.M.	Disable	(Enable 17-23)
0	1	0-6 A.M.	Enable	(Disable 17-23)
1	1	N/A	Disable	

```

IF ((TODAY.EQ.1).AND.(TOMRW.EQ.1)) GOTO 300
IF ((TODAY.EQ.1).AND.(TOMRW.EQ.0).AND.(ITIM.LT.7)) GOTO 300
IF ((TODAY.EQ.0).AND.(TOMRW.EQ.1).AND.(ITIM.GT.17)) GOTO 300

```

* Calculate forecasted maximum temperature and the total mass temperature rate

```

TB=OAT+2*(1.8*COS(0.2618*ITIM)+1.23*SIN(0.2618*ITIM))
1-2*(0.05*COS(0.5236*ITIM)-0.13*SIN(0.5236*ITIM))
TMAX=TB+3.367
STFAN=0.0
INIT=7-ITIM
IF (INIT.LT. 0) INIT=31-INIT
TIMV(5)=0.125*TIMV(1)+0.130*TIMV(2)+0.135*TIMV(3)+0.61*TIMV(4)

```

* Get present core temp. MASSP for ADM11A094

```

EPN(1)='AD'
EPN(2)='M1'
EPN(3)='1A'
EPN(4)='09'
EPN(5)='4'
CALL VALEPN(EPN,2,MASSP,IW,ACCERR)
IF (ACCERR.LT. 0) GOTO 520          ! PCM ACCESS ERROR

```

* Calculate estimated required fan running time

```

IF (TMAX.LE. 10.0) GOTO 218
IF (TMAX.LE. 16.0) GOTO 217
IF (TMAX.LE. 24.0) GOTO 216

```

* Default TIMV(5)=0.5 will calculate startup time STFAN
2 hrs for each 1 degree C of MASSP above 22.7C
(resp. 22.9C, 23.3C)

```

IF (TIMV(5).EQ. 0.0) TIMV(5)=0.5

```

* For TMAX > 24C

```

STFAN=(MASSP-22.7)/TIMV(5)
IF (STFAN .LT. 3.0) STFAN=3.0
IF ((STFAN.GT.12.0).AND.(MASSP.GT.23.5)) STFAN=12.0
IF ((STFAN.GT.10.0).AND.(MASSP.LE.23.5)) STFAN=10.0
GOTO 220
216  CONTINUE
C
C      * For TMAX between 16 - 24C
C      -----
MASSD=23.1
IF (TMAX .GE. 20.0) MASSD=22.9
STFAN=(MASSP-MASSD)/TIMV(5)
IF ((STFAN.GT.8.0).AND.(MASSP.GT.23.5)) STFAN=8.0
IF ((STFAN.GT.6.0).AND.(MASSP.LE.23.5)) STFAN=6.0
IF (STFAN .LT. 2.0) STFAN=2.0
GOTO 220
217  CONTINUE
C
C      * For TMAX between 10 - 16C
C      -----
MASSD=23.5
IF (TMAX .GE. 12.0) MASSD=23.3
STFAN=(MASSP-MASSD)/TIMV(5)
IF (STFAN .LT. 1.0) STFAN=1.0
IF ((STFAN.GT.5.0).AND.(MASSP.GT.23.5)) STFAN=5.0
IF ((STFAN.GT.3.0).AND.(MASSP.LE.23.5)) STFAN=3.0
GOTO 220
218  CONTINUE
C
C      * For TMAX between 0 - 10C
C      -----
STFAN=0.0
220  CONTINUE
C      * Integer to real conversion
RINIT=FLOAT(INIT)
C
C      * Determine if fans should be started now by checking
C      if estimated precooling time equals the time left
C      before 7:00
C      -----
IF (STFAN .LT. RINIT) GOTO 400          ! NO ACTION TAKEN
C
C      * Turn on ADM1.SY01 and AMD1.PC01
C      -----
EPN(1)='AD'
EPN(2)='M1'
EPN(3)='.S'
EPN(4)='YO'
EPN(5)='1'
VALUE=1.0
CALL PUTEPN(EPN,2,VALUE,IW,ACCERR)
IF (ACCERR .LT. 0) GOTO 520          ! PCM ACCESS ERROR

```

```

EPN(1)='AD'
EPN(2)='M1'
EPN(3)='.P'
EPN(4)='CO'
EPN(5)='1'
CALL PUTEPN(EPN,2,VALUE,IW,ACCERR)
IF (ACCERR .LT. 0) GOTO 520          ! PCM ACCESS ERROR

```

```

      * .PC01 has been turned on - store MASSP, RINIT
      -----

```

```

OPEN (UNIT=2, NAME='SY:DCEXEC.STR', TYPE='OLD',
1 FORM='FORMATTED')
CLOSE (UNIT=2, DISPOSE='DELETE')
OPEN (UNIT=2, NAME='SY:DCEXEC.STR', TYPE='NEW',
1 FORM='FORMATTED')
WRITE (2,230) MASSP,RINIT
FORMAT(1X,2F12.4)

```

```

*****7:00 PRECOOLING TERMINATION ROUTINE*****
      -----

```

```

CONTINUE

```

```

      * If not 7:00 skip this routine
      -----

```

```

IF (ITIM .NE. 7) GOTO 400          ! SKIP
IF (PC01 .EQ. 0.0) GOTO 400       ! SKIP

```

```

      * At 7:00 turn precooling switch off
      -----

```

```

EPN(1)='AD'
EPN(2)='M1'
EPN(3)='.P'
EPN(4)='CO'
EPN(5)='1'
VALUE=0.0
CALL PUTEPN(EPN,2,VALUE,IW,ACCERR)
IF (ACCERR .LT. 0) GOTO 520          ! PCM ACCESS ERROR

```

```

      * Get core temp. reading for ADM11A094
      -----

```

```

EPN(1)='AD'
EPN(2)='M1'
EPN(3)='1A'
EPN(4)='09'
EPN(5)='4'
CALL VALEPN(EPN,2,MASS7,IW,ACCERR)
IF (ACCERR .LT. 0) GOTO 520          ! PCM ACCESS ERROR

```

```

      * Retrieve MASSP and RINIT from storage
      -----

```

```

OPEN (UNIT=2, NAME='SY:DCEXEC.STR', TYPE='OLD',
1 FORM='FORMATTED')
READ (2,230) MASSP,RINIT
CLOSE (UNIT=2, DISPOSE='SAVE')
IF (RINIT .EQ. 0.0) RINIT=0.1

```

C
C
C

```

      * Calculate new value for TIMV(5)
      -----

```

```

TIMV(5)=(MASSP-MASS7)/RINIT

```

C
C
C

```

      * Update TIMV
      -----

```

```

OPEN (UNIT=2, NAME='SY:TIMV.STR', TYPE='OLD',
1 FORM='FORMATTED')
READ(2,5) (TIMV(J),J=1,4)
CLOSE(UNIT=2, DISPOSE='DELETE')
DO 330 J=1,4
TIMV(J)=TIMV(J+1)

```

330

```

CONTINUE
OPEN (UNIT=2, NAME='SY:TIMV.STR', TYPE='NEW',
1 FORM='FORMATTED')
WRITE (2,5) (TIMV(J),J=1,4)
CLOSE (UNIT=2, DISPOSE='SAVE')

```

C
C

```

CLOSE (UNIT=3, DISPOSE='SAVE')
STOP

```

C
C
C
C

```

      * Error stops
      -----

```

500

```

TYPE 510

```

510

```

FORMAT(/' DYNCON -- DATABASE ACCESS ERROR !')

```

```

STOP

```

520

```

TYPE 530

```

530

```

FORMAT(/' DYNCON -- PCM ACCESS ERROR !')

```

```

STOP

```

```

END

```

C
C
C
C
C
C
C
C
C
C
C

```

#####
SUBROUTINE HOLIDAY
-----

```

```

Thos subroutine calculates holiday indicators for
TODAY and TOMMORROW.
#####

```

```

SUBROUTINE HOLIDAY(TODAY,TOMRW)

```

```

INTEGER*2 TODAY,TOMRW,DAY,MON,YR,FDAY,FMON,FYR,WD,FWD,ASOC
LOGICAL*1 HOLDS(31)

```


C
C
C
C
CALL ,IDATE(MON, DAY, YR)

** Find the date for tomorrow

IF (DAY .LT. 28) GOTO 100
IF ((DAY .EQ. 28).AND.(MON .EQ. 2)) GOTO 90
IF ((DAY .EQ. 29).AND.(MON .EQ. 2)) GOTO 95
IF (DAY .LT. 29) GOTO 100
IF (DAY .EQ. 30) GOTO 80

C
C
C
* 31-day months: Jan, Mar, May, Jul, Aug, Oct, Dec

FMON=0
IF (MON .EQ. 1) FMON=2
IF (MON .EQ. 3) FMON=4
IF (MON .EQ. 5) FMON=6
IF (MON .EQ. 7) FMON=8
IF (MON .EQ. 8) FMON=9
IF (MON .EQ. 10) FMON=11
IF (MON .EQ. 12) GOTO 10
FDAY=1
FYR=YR
GOTO 150

C
C
C
* December 31

10 CONTINUE
FDAY=1
FMON=1
FYR=YR+1
GOTO 150

C
C
C
* 30-day months: Apr, June, Sept, Nov

80 CONTINUE
IF (MON .EQ. 4) GOTO 85
IF (MON .EQ. 6) GOTO 85
IF (MON .EQ. 9) GOTO 85
IF (MON .EQ. 11) GOTO 85
GOTO 100

85 CONTINUE
IF (MON .EQ. 4) FMON=5
IF (MON .EQ. 6) FMON=7
IF (MON .EQ. 9) FMON=10
IF (MON .EQ. 11) FMON=12
FDAY=1
FYR=YR
GOTO 150

C
C
C
* 28-Feb and not a leap year

```

90      CONTINUE
      IF (YR .EQ. 88) GOTO 100
      IF (YR .EQ. 92) GOTO 100
      IF (YR .EQ. 96) GOTO 100
95      CONTINUE
      FMON=3
      FDAY=1
      FYR=YR
      GOTO 150
100     CONTINUE
      FDAY=DAY+1
      FMON=MON
      FYR=YR
150     CONTINUE
C
C      * Read holiday table from the "Optimization" data
C      file 'EMC.DAT' and find holiday indicators for
C      today and tomorrow.
C
C      Holidays in EMC.DAT : 0=no holiday, -1=holiday
C
OPEN(UNIT=3,NAME='SY:[321,54]EMC.DAT',TYPE='OLD',
1ACCESS='DIRECT',RECORDSIZE=12,ERR=200,MAXREC=1500,
1ASSOCIATEVARIABLE=ASOC,READONLY)
J=1441+MON                                ! REFERENCE - EMC.FTN
READ(3'J,ERR=200)HOLS
TODAY=(-1)*HOLS(DAY)
J=1441+FMON
READ(3'J,ERR=200)HOLS
TOMRW=(-1)*HOLS(FDAY)
CLOSE (UNIT=3, DISPOSE='SAVE')
C
C      * Find weekday for today and tomorrow
C      -----
CALL WKDAY(WD,DAY,MON,YR)
CALL WKDAY(FWD,FDAY,FMON,FYR)
IF ((WD.EQ.1).OR.(WD.EQ.7)) TODAY=1
IF ((FWD.EQ.1).OR.(FWD.EQ.7)) TOMRW=1
RETURN
C
C      * Error returns - If EMC.DAT missing or corrupted
C      return no holiday status for today and tomrw
C      and type a warning message.
C      -----
200     CONTINUE
      TODAY=0
      TOMRW=0
      TYPE 208
210     FORMAT(' DYNCON -- EMC.DAT MISSING OR CORRUPTED !')
      RETURN
      END
C

```

```
C C C C C C C C C C
SUBROUTINE WEEKDAY

      This subroutine computes the day of the week.

#####

SUBROUTINE WKDAY(IWD,IDAY,IMON,IYR)

      INTEGER*2 IWD,IDAY,IMON,IYR
      REAL*4 WD, DAY, MON, YR


      DAY=FLOAT(IDAY)
      MON=FLOAT(IMON)
      YR =FLOAT(IYR)
      YR=1900.+YR
      WD=2.                                ! MONDAY, 01-JAN-1900
      WD=WD+DAY                            ! DAY OF MONTH
      IF (MON .LE. 2.) WD=WD+((YR-1.)/4.) ! LEAP YEARS
      IF (MON .GE. 3.) WD=WD+(YR/4.)
      IF (MON .GT. 1.) WD=WD+3.            ! JANUARY
      IF (MON .GT. 2.) WD=WD+0.            ! FEBRUARY
      IF (MON .GT. 3.) WD=WD+3.            ! MARCH
      IF (MON .GT. 4.) WD=WD+2.            ! APRIL
      IF (MON .GT. 5.) WD=WD+3.            ! MAY
      IF (MON .GT. 6.) WD=WD+2.            ! JUNE
      IF (MON .GT. 7.) WD=WD+3.            ! JULY
      IF (MON .GT. 8.) WD=WD+3.            ! AUGUST
      IF (MON .GT. 9.) WD=WD+2.            ! SEPTEMBER
      IF (MON .GT.10.) WD=WD+3.            ! OCTOBER
      IF (MON .GT.11.) WD=WD+2.            ! NOVEMBER
      IF (MON .GT.12.) WD=WD+3.            ! DECEMBER
      WD=WD+YR                             ! YEAR
      WD=WD+3.                             ! OFFSET SO SUNDAY=1
      WD=1.+WD-(7.*(IFIX(WD/7.)))
      IWD=IFIX(WD)
      RETURN
END
```

**APPENDIX A-5: Questionnaire for Administration Building
Occupants**

Dear Employee at the Administration Building:

As of May this year, the Department of Physical Plant has been using a new control program. This program has altered the manner in which the heating and ventilating system is used in the Administration Building. We are interested in knowing how this new program has influenced your comfort in the building.

In your opinion, how have you found the level of comfort in your work area from May to October of 1984 compared to May to October of 1983?

More acceptable __

No significant change.....__

Less acceptable __

Don't know __

Thank you for your time.

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